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PROJEKTRAPPORTER

VIND-96/11

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Utvärdering av Lyse vindkraftstation 1992-1995
Slutrapport
Evaluation of Lyse wind power station 1992-1995
Final report

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Slutrapport.
Evaluation of Lyse Wind Power Station 1992 - 1995
Final Report

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RAPPORT INOM OMRÅDET VINDKRAFT

Rapportnummer: VIND-96/11

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LYSE VINDKRAFT

Slutrapport

Utvärdering av Lyse Vindkraftstation 1992-1995

Final Report

Evaluation of Lyse Wind Power Station 1992-1995

Finansierad av
Vattenfall, Elforsk(SEU) och Nutek

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0. SAMMANFATTNING PÅ SVENSKA

0.1 RAPPORTERING

Rapporteringen av erfarenheterna från Lyse vindkraftstation består av två olika rapporter, dels en Huvudrapport+Bilagor samt dels föreliggande sammanfattande Slutrapport. Den senare skall vara en relativt utförlig sammanfattning som redovisar öppen information från Huvudrapporten.

Slutrapporten har sammanställts av Sven-Erik Thor på FFA. Vid det arbetet har text och värdefulla kommentarer erhållits från följande personer:

Göran Dalén	Vattenfall AB
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Staffan Engström	Nordic Wind Power
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Projektet presenterades vid ett seminarium på Vattenfall den 5:e oktober, samt vid Vindenergisymposiet i Stockholm den 7-8:e november 1995.

0.2 BAKGRUND

Vattenfall AB har med bidrag från NUTEK och Elforsk AB uppfört och drivit Lyse vindkraftstation sedan 1992. Avsikten har varit att utveckla och pröva en föreslagen ny vindkraftteknik med låg vikt, enkel teknik och kostnadseffektiv reglering. För att få en bra jämförelse mellan den nya tekniken och befintlig serietillverkad teknik uppfördes inte bara det nya "utvecklingsaggregatet", NWP 400 (Nordic 400), utan även ett danskt "standardaggregat" av ungefär samma storlek, Bonus 450 MkII.

Tidigare erfarenhet med utvecklingsverksamhet inom vindkraftområdet har visat på svårigheten att förklara den låga tillgängligheten hos prototyper. Dessa kommer alltid att drabbas av tekniska problem, vilka leder till långa stilleståndstider. Ett vindkraftverk som står stilla trots att det blåser leder alltid till frågor. En kombination av ny och beprövad teknik har i detta projekt givit möjlighet att se hur olika aggregat fungerar, samtidigt som teknikutveckling sker.

I projektet har också ingått att kartlägga tekniska beteenden samt vindförutsättningar vid ett västkustläge, och att ta reda på hur vindkraftstationen upplevs av närboende med avseende på ljud och inverkan på landskapsbild.

Grundfilosofin vid utvecklingen av NWP 400 har varit att minimera laster och påkänningar dels genom att den tvåbladiga turbinen fästs vid axeln med en gungled, dels genom en vek och dämpad koppling mellan maskinhus och torn. Låga laster gör det möjligt att få ned totalvikten och därmed tillverkningskostnaden för aggregatet. Dessutom har överstegringsreglering ("stallreglering") valts för att få en enkel turbinkonstruktion, och variabelt varvtal för att minska aerodynamiskt ljud och för att utvinna mesta möjliga energi. Bonus 450 MkII har en konstruktion som är vanlig i danska vindkraftaggregat: tre blad, överstegringsreglering, stelt nav, fast varvtal.

Jämförelser med andra aggregat i samma storleksklass visar att NWP 400 är betydligt lättare. Totala vikten för NWP 400 är 29 ton inklusive torn. Motsvarande siffra för Bonus 450 Mk II är 42 ton. Ett annat sätt att jämföra aggregaten är att beräkna vikten för aggregaten exklusive torn och fundament och dividera med svept rotorarea. En jämförelse av dessa värden visar att NWP 400 är 30-37% lättare än Bonus 450 MkII.

Lätta vindkraftverk förväntas i framtiden leda till lägre tillverkningskostnad och i förlängningen till en lägre kostnad per producerad kWh, förutsatt att tekniken fungerar med hög tillgänglighet. Avsikten med detta projekt är att undersöka och verifiera denna teknik. En ytterligare förutsättning för val av konstruktionslösningar var att de skulle kunna skalas upp till större aggregatstorlekar.

Båda aggregaten togs i drift under 1992. Bonus 450 MkII har sedan dess varit i drift hela tiden, med hög tillgänglighet, och med för denna aggregattyp normala fel. En justering som införts är att reglersystemet anpassats för att bättre klara vindförhållandena på västkusten med mer turbulent vind än i typiska danska lägen för vindkraftverk.

NWP 400 behövde ett antal justeringar och modifikationer innan det togs över av Vattenfall och under 1995 sattes i normal produktion. Även under perioden före övertagandet var dock aggregatet i drift större delen av tiden och mätningar och utvärdering av aggregatet påbörjades 1992. En komplettering som tidigt infördes var extra filter i det elektriska frekvensomvandlingssystem som används för att göra drift med variabelt varvtal möjlig. Kraftelektroniken alstrade övertoner som störde Bonus 450 MkII. Dessa övertonsstörningar försvann sedan filtren införts.

Under 1993 skadades ett blad då det slog in i tornet. Det visade sig att bladutböjningen för turbinen vid höga vindhastigheter blev så stor att bladen kunde träffa tornet under vissa driftsituationer. För att minska gungrörelserna har vissa modifikationer införts. Därtill stoppas aggregatet vid stora gungvinklar. Detta har medfört ett visst produktionsbortfall, se vidare kapitel 2.

Aggregaten har utvärderats i enlighet med ett omfattande program. Produktionsförmåga, driftserfarenheter, hur aggregaten samverkar med kraftnätet samt omgivningspåverkan har undersökts för båda aggregaten. För NWP 400 har dessutom produktionsförmåga, aerodynamik, laster under drift samt säkerhet mot utmattning analyserats. Samverkan med personal från den svenska vindenergiforskningen har varit värdefull vid detta arbete.

För att kunna genomföra den planerade utvärderingen av aggregaten försågs de med ett mätsystem för kontinuerliga registreringar av vind- och produktionsdata. NWP 400 försågs även med givare för töjningar, rörelser och andra data som definierar driftstillståndet i aggregatet. Mätsystemet har tyvärr drabbats av en del driftsstörningar och problem som begränsat möjligheterna till långtidsuppföljningar av olika faktorer. Modifieringar har dessutom i efterhand införts på NWP 400, vilket inneburit att det endast för en begränsad tid mot slutet av utvärderingen gått att genomföra rättvisande jämförande studier av aggregaten. Det finns dock en mycket stor mängd data registrerade för olika typer av situationer, data som kan vara av stort värde för att analysera aggregatet och för att verifiera de beräkningsmodeller som använts. Mycket av det materialet kommer att vara värdefullt för Vindkraftskonsortiets fortsatta forskning och utveckling kring den "svenska linjen" med lätta och flexibla aggregat.

0.3 PRODUKTIONSRESULTAT OCH ERFARENHETER FRÅN DRIFTEN

Bonus 450 MkII har varit i drift med små störningar sedan det togs i drift i juni 1992. Det har under de första tre åren t o m juni 1995 producerat 2 893 MWh, vilket innebär att det inte nått upp till den förväntade genomsnittliga årsproduktionen. Driften stördes inledningsvis av att kontrollsystemet dels var känsligt för turbulent vind så att aggregatet inte kopplades in vid oroliga vindförhållanden, dels av att övertoner på nätet störde kontrollsystemet. Störningarna upphörde sedan kontrollsystemet justerats och ett extra övertonsfilter införts på NWP 400.

NWP 400 är ett utvecklingsaggregat för att prova nya tekniska lösningar. Det har därför varit naturligt att det uppstått en del tekniska problem, att driften störts och att modifieringar och justeringar varit nödvändiga. Det återstår en del problem, som stör driften och hindrar aggregatet att nå upp till önskat produktionsresultat. Totalt sedan starten, den 15:e september 1992, har aggregatet producerat 1060MWh, till och med juni 1995.

En stor del av perioden har driften delvis varit inskränkt p g a intrimning, justeringar eller driftsinskränkningar i avvaktan på reparationer eller modifieringar. Inte heller i dag (juni 1995) når aggregatet upp till förväntad produktion p g a att det av säkerhetsskäl stängs av när rörelserna i gungleden blir för stora.

En mer noggrann analys av produktion och drift för båda aggregaten har mot denna bakgrund endast gjorts i den senare delen av utvärderingsperioden, under 12-månadersperioden juni 1994 - maj 1995.

Under denna period har följande produktionssiffror uppnåtts:

Produktion 450 MkII:	1092.3 MWh
Medelproduktion vid inkoppling till nät:	177 kW
Medelproduktion per kalendertid:	125 kW
Tidstillgänglighet:	93 %

Produktion NWP 400:	696.5 MWh
Medelproduktion vid inkoppling till nät:	132 kW
Medelproduktion per kalendertid:	80 kW
Tidstillgänglighet:	82 %

Den lägre produktionssiffran för NWP 400 förklaras av ovannämnda problem med driften. Närmare studie av tillgänglighetsstatistiken visar att 532 timmar =6.1% föll bort på grund av stor gungvinkel. Till detta bör läggas 138 timmars stopp för hög vind (stoppgränsen har varit nedställd), dvs totalt 7.6%. Detta motsvarar att produktionen reduceras från 1016 till 850 MWh. Resterande otillgänglighet utgjorde 1100 timmar, totalt ger detta en tillgänglighet av 87%. vilket reducerar produktionen till 740 MWh. Resterande förklaras av osäkerheten i vind/effekt-kurvan.

Den relativt låga tillgängligheten för Bonus 450 MkII i jämförelse med andra kommersiella aggregat beror huvudsakligen på problem med kontrollsystem, stopp p.g.a överproduktion och problem med oljeöverföring till navet. Om man tar bort dessa orsaker får man en tillgänglighet på 98 %.

0.4 TEKNISK UTVÄRDERING

Grundläggande krav på ett vindkraftverk är att det till lägsta kostnad utvinner så mycket energi som möjligt ut vinden, att det är dimensionerat så att det är säkert för omgivningen och klarar de varierande laster det utsätts för, att det inte förorsakar störningar i kraftnätet, samt att det har ett kontrollsystem som klarar de olika driftsituationer som uppstår. Målet för den tekniska delen av utvärderingsprogrammet har i första hand varit att undersöka hur väl de nya tekniska lösningarna hos NWP 400 fungerar. För det danska aggregatet har den tekniska utvärderingen inskränkts till att mäta produktionsförmågan, ljud samt hur väl aggregatet samverkar med kraftnätet, som en del i den allmänna jämförelsen mellan de två aggregaten.

0.4.1 Produktionsförmåga

Produktionsförmågan, aggregatets förmåga att utvinna energi ur vinden, kan uttryckas på flera sätt: med en vind-effektkurva som visar uteffekten vid olika vindhastigheter, med en uppskattad årsproduktion vid angivna vindförutsättningar, eller som en beräknad medeleffekt under året. För ingående jämförelser av två aggregat kan även turbinens verkningsgrad i uttryckas som s k C_p-λ-kurvor. Det senare förutsätter dock att det mekaniska momentet för det roterande systemet kan mätas på ett tillfredsställande sätt, vilket är svårt för NWP 400 med dess konstruktion.

Båda verkens produktionsförmåga har undersökts utgående från mätningar av vindhastighet och levererad effekt under tiden oktober - december 1994. Ur mätdata har vind-effektkurvor bestämts i enlighet med en av IEA standardiserad metod, och ur dessa har årsproduktion och medelproduktion beräknats. Skälet till att en så kort tid valts för jämförelsen är en ambition att få en rättvisande jämförelse där båda aggregaten utsatts för samma vindförhållanden, varit i drift hela tiden och inga modifieringar gjorts.

Den beräknade årsproduktionen för NWP 400, som det körts under uppföljningsperioden (vindintervallet 4.25-15.75 m/s) och förutsatt att inga driftsstörningar inträffar, är 1030 MWh, och medel-effekten från aggregatet är 118 kW, räknat över årets alla timmar. Vinden förutsätts ha en medelvindhastighet på 7,5 m/s och vara Rayleighfördelad. Osäkerheten i uppskattad årsproduktion är ± 85 MWh och i effekten ± 10 kW.

Den enligt leveranskontraktet beräknade årsproduktionen för NWP 400 är 1096 MWh. Under perioden har aggregatet stängts av vid vindhastigheten 15,75 m/s istället för vid avsedda 23 m/s för att minska risken för att bladen träffar tornet vid stora rörelser i gungnavet. Med denna begränsning skulle årsproduktionen enligt kontraktet vara 1003 MWh. Under dessa förutsättningar har aggregatet producerat mer än förväntat.

Den beräknade årsproduktionen för Bonus 450 MkII är 1160 ± 95 MWh och medelproduktionen 132 ± 11 kW. Årsproduktionen skall enligt kontraktet vara 1227 MWh.

NWP 400 producerar, vid vindhastigheter under 6 m/s, bättre än Bonus 450 MkII. Detta förklaras av den bättre systemverkningsgraden som erhålles vid variabelt varvtal.

Slutsatsen av uppföljningen av aggregatens produktionsförmåga är att mätningarna styrker att aggregaten ger den förväntade produktionen. Mätningarna är dock behäftade med en viss osäkerhet, eftersom den period då båda varit i drift samtidigt och ej modifierats är relativt kort.

0.4.2 Laster, påkänningar, utmattning

En viktig del i utvärderingen av NWP 400 har varit att undersöka om aggregatet med sina nya tekniska lösningar fungerar på det sätt som kan förväntas enligt de beräkningar som legat till grund för konstruktionen. Bonus 450 MkII är ett serietillverkat aggregat som konstruerats i enlighet med tidigare erfarenhetsvärden och det har därför inte ingått i utvärderingen att göra en sådan uppföljning.

För att kunna mäta laster och utböjningar i blad, maskinhus och torn utrustades NWP 400 med givare för krafter, moment och accelerationer i blad, maskinhus och torn. Mätvärdena har registrerats tillsammans med uppgifter om vinden och om aggregatdriften för att ge underlag för beräkningar av bl a egenfrekvenser, laster, påkänningar och säkerhet mot utmattning. De uppmätta egenfrekvenserna för blad och torn stämmer väl med de beräknade. Varken i förväg kända kopplingar mellan svängningsmoder eller andra egenfrekvenser förväntas ge några problem för aggregatet. Beräknade laster och rörelser hos aggregatet ligger väl inom de förväntade områdena. Uppmätta vindförhållanden har inte visat sig svårare än det vindunderlag som användes vid konstruktionsberäkningarna. Aggregatet bedöms klara uppställda krav på säkerhet mot utmattning.

Speciell uppmärksamhet har ägnats åt att dels analysera förhållanden vid girning (sidvridning), dels undersöka dynamiken i gungleden. En viktig del i konstruktionen av NWP 400 är kombinationen av överstegringsreglering med gungled och girdynamik samt variabelt varvtal. Dämpning och fjädring i girsystemet motsvarar förväntningarna. Däremot har styrningen av girningen ej helt fungerat som avsett, vilket kan ha bidragit till de stora gungrörelser som inträffat vid hög vind. Gungrörelserna i turbinen ökar vid 13 m/s.

Under 1993 skadades som tidigare nämnts ett blad när det vid stora gungrörelser slog i tornet. En orsak var att bladen var vekare än vad som antagits i de dynamiska beräkningarna. Detta resulterade i att bladen vid vissa extrema driftsituationer exiterades på ett sådant sätt att bladrörelserna blev större än förväntat. För att minska rörelserna och risken för haveri har flera modifikationer införts, bland annat stoppas aggregatet vid stora gungvinklar. Analyser av problemet har visat olika vägar att ytterligare minska rörelserna och därmed omfattningen av stopp på grund av för stora gungrörelser. Erfarenheterna från utvärderingen har kommit till nytta vid konstruktionen av det större aggregatet NWP 1000 (1000kW) som har tagits i drift vid Näsudden under sommaren 1995.

0.4.3 Samverkan med kraftnätet

Produktionen från ett vindkraftverk kan variera snabbt beroende på vindhastigheten. Krav på verket är att dessa variationer ej får ge otillåtna störningar i kraftnätet, liksom att in- och urkoppling endast får ge upphov till små spännings- och strömvariationer. Mätningar av strömmar och spänningar har främst gjorts vid den för aggregaten gemensamma anslutningspunkten till nätet. Mätningarna har gjorts enligt rekommendationen från IEA.

Aggregaten har visat sig ha liten påverkan på nätet vid drift, och inkopplingarna gav acceptabla störningar. Det största spänningsfallet, 3%, uppstod vid inkoppling av Bonus 450 MkII.

Kraftelektroniken som omvandlar den variabla frekvensen från NWP 400 till nätets frekvens ger övertoner i ström och spänning till nätet. Särskild uppmärksamhet har riktats mot dessa. För två av de registrerade övertonerna överskrids Vattenfalls interna rekommendationer för tillåtet övertonsinnehåll. Överskridandena var dock måttliga och inträffade då NWP 400 var i drift med låg effekt och de har liten betydelse för nätet.

Däremot förorsakade övertonerna inledningsvis en del störningar i funktionen hos Bonus 450 MkII kontrollsystem vilket ledde till oönskade stopp. Dessa försvann efter installation av det extra filtret. En långtidsövervakning av förekomsten av korta spänningsfall i nätet visade att detta inträffade vid ett antal tillfällen, men att störningarna kom från nätet, ej från aggregaten.

0.4.4 Reglersystemets funktion

En utvärdering av reglersystemets funktion ingick ursprungligen i programmet för utvärderingen av NWP 400. Reglersystemet är en central funktion i den tekniska lösningen med variabelt varvtal, gungled och överstegringsreglering.

Tyvärr visade det sig att utvärderingen blev försenad på grund av mätsvårigheter.

Erfarenheterna från driften och annan uppföljning visar dock att aggregatet i stort fungerar som avsett och klarar de vindförändringar och störningar i nätet som förelegat, kanske med undantag för girregleringen där analyserna av gungrörelserna indikerat att girregleringen ej helt fungerat som avsett vid hastiga förändringar i vindhastighet och vindriktning.

0.4.5 Speciella försök

Ett antal speciella frågeställningar som främst rör aerodynamiska egenskaper och hur dessa hänger samman med aggregatdynamik och laster har undersökts i några mätningar och försök för NWP 400. Frågor som undersökts är inverkan av bladinställning, aerodynamiska egenskaper hos bladen och inverkan av ”stall strips”[1].

En frekvensanalys av uteffekten 1994 visade en störning av samma frekvens som turbinens rotation. Den visade sig bero på en skillnad i injustering av bladvinklarna (-2,2 och -1,7°). En justering av båda bladen till en mindre vinkel (-0,8°) gav en minskad störning, men gav dessutom högre toppeffekt och snabba oönskade effekttoppar vid höga vindhastigheter. För att åtgärda detta monterades nya ”stall strips” som fick önskad effekt, men sänkte märkeffekten mer än önskat. En fortsatt intrimning förväntas kunna ge en ökad produktion samtidigt som effekttopparna blir acceptabla.

Aggregatplacerade givare för vindhastighet, vindriktning och effekt har undersökts och kalibrerats mot mätsystemets givare. Givaren för vindriktning gav en signal med stor osäkerhet. De övriga kunde kalibreras med tillfredsställande noggrannhet för att kunna användas för mätningar och utvärderingar.

0.4.6 Vindmätningar

Vindförutsättningarna vid aggregatplatsen har undersökts av MIUU genom mätningar av vindhastighet, vindriktning och temperatur i fem nivåer upp till 65 m höjd i en särskild vindmätningsmast placerad mellan aggregaten. Även luftfuktighet och lufttryck har mätts löpande. Utvärderingen har baserats på mätningar från juni 1993 till mars 1995. Signalerna registrerades med hjälp av MIUU egna mätsystem och levererades vidare till det övergripande mätsystemet. Medelvinden på navhöjd (50 m över havet) är uppmätt till 7.2 m/s. Normalårskorrigerat blir det 6.5 m/s.

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[1] “Stall strip” är en anordning (liten vinkelprofil) som monteras på bladens framkant. Anordningen används för att minska maximal lyftkraft på delar av bladet.

Mätningarna har visat att vinden var mindre turbulent än väntat för detta läge med omgivande öar och bergig terräng. Vinden från havsriktningen motsvarade ungefär en vind som kan förväntas över en plan grässlätt, och vinden från land ungefär vad som kan vara normalt inom ett normalt jordbrukslandskap med häckar, spridda byggnader och byar.

En uppskattning av medelvindhastigheten vid Lyse jämfört med medelvinden vid Måseskär, ett fritt havsläge, visar att den vid Lyse är 9% lägre på 65 m höjd och 21% lägre på 25 m höjd.

I detta sammanhang måste det påpekas att man vid vissa vindriktningar har erhållit korvariga vindsituationer med hög turbulens och vindskjuvning.

0.5 PÅVERKAN PÅ OMGIVNINGEN

Vindkraftverk påverkar omgivningen främst genom det ljud som alstras från blad och maskineri samt genom att de förändrar landskapsbilden. De kan dessutom ibland störa överföringen av elektromagnetiska vågor, som TV, radio och radarsignaler. Dessa frågor har tidigare undersökts ingående vid svenska prototypaggregat, tex vid Maglarp och Näsudden I. Vid Lyse vindkraftstation har mätningar gjorts för att ta reda på hur stora dessa störningar är i aggregatens omgivning, samt hur vindkraftverken upplevs av de närboende.

Ingen inverkan på fågellivet har rapporterats, men fåglar har förorsakat ett antal skador på meteorologernas vindhastighetsgivare.

0.5.1 Ljud

Vindkraftverk alstrar ljud dels i form av aerodynamiskt ljud från turbinbladen, vars spetsar rör sig med hög hastighet genom luften, dels genom mekaniskt ljud från maskineriet, där växel, generator, fläktar och pumpar avger ljud.

Det ljud som sänds ut från aggregaten har mätts i s k ljudemissionsmätningar, där aggregaten körts var för sig. Dessa mätningar visar att det sammanvägda utsända ljudet ligger något högre för NWP 400 än för Bonus 450 MkII, beroende på ett högre maskinljud. Vid 8 m/s är ljudtrycksnivån 2 dB(A) högre från NWP 400. Skillnaden är dock inte beroende av NWP 400 principiella konstruktion, utan bör kunna reduceras i en seriemaskin.

Det ljud som verkligen uppfattas vid olika platser har också mätts upp och jämförts med i förväg förväntade värden för tre platser på ett avstånd av 4-500 m från aggregaten. Mätningarna visade att ljudtrycksnivåerna var låga och stämde väl med beräknade värden.

0.5.2 Inverkan på TV-mottagning

Mätningar av störningar på TV-signaler har gjorts vid närliggande bebyggelse. Mätvärden och bildkvalitet påverkades där ej av vindkraftverken. Nära aggregaten, på avståndet 100-300 m, fanns det starka till måttliga störningar av bild och ljud, starkast när signalen passerade förbi torn och turbin. Inom detta område vistas eller bor inga personer stadigvarande.

0.5.3 Inställning till vindkraft hos närboende

En intervjuundersökning har genomförts med 20 permanentboende personer från Skalhamn samt med 24 sommarboende i Ramsvik. Bostadens avstånd till vindkraftstationen varierade för dessa personer mellan 300 och 4000 meter. Dessutom fanns en referensgrupp bestående av personer från Lysekils kommun.

Det är tydligt att Lyse Vindkraftstation bidragit till ett ökat intresse för vindkraft i Lysekils kommun. I Ramsvik finns en mer uttalad tvekan inför vindkraftens etablering i den omedelbara semestermiljön. Denna tvekan skulle kunna elimineras genom en tydligare produktionsredovisning så att man ser nyttan av vindkraftverken. Ett annat, efterfrågat, sätt vore att leverera elenergin direkt till de som bor i närheten av vindkraftverk om detta vore tekniskt möjligt.

I samtliga undersökningsgrupper betonas det att vindkraftslokalisering skall ske i lämpliga områden, där den inte kan uppfattas som störande. Vissa känsliga områden måste få förbli ostörda. Det är viktigt att finna plats åt vindkraften i samråd med berörd befolkning. Mindre grupper av vindkraftverk är tänkbara, dock inte större gruppstationer. Tekniken måste utvecklas så att vindkraftverken verkligen fungerar och producerar energi.

Ljudstörningar har rapporteras från Ramsvik, dock kan inget samband fastställas mellan boendeavstånd och störning. Reflexer från omgivande klippor kan spela en stor roll i hur man upplever ljudet. Rapporterade ljudstörningar sammanfaller med en tveksam inställning till vindkraften i boendemiljöns omedelbara närhet.

En klar majoritet av de intervjuade anser sig positivt inställda till vindkraften som en miljövänlig och kompletterade energikälla. Det är viktigt att informera om vad som krävs av de områden som kan bli aktuella för vindenergiproduktion samt vilka områden detta kan tänkas bli. Vidare är det viktigt att informera om varför ett svenskt utvecklingsverk har placerats bredvid ett välutvecklat och beprövat danskt vindkraftverk. Samarbetet med turistbyrån i Lysekil bör utvecklas och informationsbyggnaden hållas mer öppen. Vindkraften bör presenteras som ett komplement och de rådande ekonomiska förhållandena bör redovisas. Nyttovärderingar har starkast präglat åsikterna och erfarenheterna hos den bofasta befolkningen. En del av preferenserna angående design hos vindkraftverken har tydligt samband med hindertid. Det är dock tydligt att tre turbinblad föredras av de flesta i denna undersökning. Hindermarkeringar innebär inga påtalade störningar. Vattenfall har upplevts som ett seriöst företag och man anser att samarbetet med kommunen och informationsverksamheten i stort fungerat bra.

0.6 SLUTSATSER

Tekniken fungerar, men vissa modifikationer behövs

Den främsta avsikten med projektet har varit att prova och utvärdera en ny vindkraftteknik, dels i detaljerade mätningar på NWP 400, dels i jämförelser med det danska standardaggregatet. Samtidigt har det varit ett krav att anläggningen med sina båda aggregat skall gå som en produktionsanläggning sedan utvärderingen genomförts.

Den samlade slutsatsen av driften, och av de olika mätningar och uppföljningar som genomförts, är att den nya tekniken fungerar på avsett sätt och att de beräkningar som gjordes i samband med konstruktionsarbetet stämmt väl. Utvärderingen styrker att aggregatet kan ge förväntad produktion, att det klarar olika driftssituationer, och att det kan förväntas klara laster och uppställda krav med avseende på säkerhet mot utmattning. Grundlösningarna har senare använts i det nya större aggregat, NWP 1000, som Vattenfall uppfört på Näsudden på Gotland.

Ett resultat av utvärderingen är också att den visat att de beräkningshjälpmedel som använts för att dimensionera aggregatet och beräkna produktionsförmågan givit riktiga resultat respektive goda uppskattningar.

Vissa dellösningar har dock ej fungerat som avsett, och har därför behövt modifieras. Ytterligare förändringar kan vara motiverade vid en serietillverkning av NWP 400. Aggregatet har i nuvarande utförande svårigheter vid höga vindhastigheter på grund av risk för skador vid stora gungrörelser. Förändringar har gjorts för att minska risken för att ett blad skall slå in i tornet, men trots detta är gungrörelserna ibland stora. Med ytterligare modifieringar bör det enligt beräkningar gå att minska gungrörelserna och därmed öka tillgängligheten för aggregatet.

Jämförelsen mellan aggregaten visar främst att båda aggregaten ungefär nått förväntad produktionsförmåga. Eftersom det ena aggregatet är ett standardaggregat och det andra ett utvecklingsaggregat och det första av sitt slag, går det inte att dra några djupare slutsatser om skillnader i produktionsförmåga, tillgänglighet eller kostnader. NWP 400 har haft fler driftsavbrott, ger något mer övertoner till nätet och avger något mer ljud – men utvärderingen visar inte några hinder för att rätta till dessa brister till en senare version.

0. SUMMARY IN ENGLISH

0.1 REPORTING

The experience gained at Lyse Wind Power Station will be presented in two different reports, a Main Report and its appendices and this Summary Report. The latter is a relatively comprehensive summary which will present open information from the Main Report.

The Final Report has been compiled by Sven-Erik Thor at FFA. Text and valuable comments have been contributed by the following:

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Christer Kronstrand	Vattenfall Regionnät AB
Staffan Engström	Nordic Wind Power
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Sven Ruin	Nordic Wind Power
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Maria Poppen	FFA

The project was presented in a seminar at Vattenfall on the 5th of October and at the Swedish Wind Energy Conference in Stockholm 7-8:th of November 1995.

0.2 BACKGROUND

Vattenfall AB erected Lyse Wind Power Station in 1992 and has been running it since then with grants from NUTEK (Swedish National Board for Industrial and Technical Development) and Elforsk AB. The aim has been to develop and test a proposed new wind power technique with low weight, simple technology, and cost-effective control. For the sake of comparison between the new concept and existing, series-manufactured technology, a Danish "standard" unit of approximately the same size, a Bonus 450 MkII, was erected as well as the new "development" unit, the NWP 400.

Early development projects within the wind energy field has had difficulties in explaining the low availability of prototypes. They will always have technical problems leading to poor availability. A wind power plant which is at stand still when it is blowing is always raising a lot of questions. A combination of new and well-proven technique, has in this project, given the possibility to investigate how different machines perform at the same time as development of the technique takes place.

The project included surveying technical features and wind conditions at a site on the west coast, and finding out how the Wind Power Station is perceived by local residents in terms of noise and its impact on the landscape.

The basic philosophy in the design of NWP 400 was to minimise loads and stresses, partly by attaching the two-bladed turbine to the shaft with a teetered hub, and partly through a soft and damped connection between the machinery housing and the tower. Low loads make it possible to reduce the total weight and thereby the manufacturing costs of the unit. Stall control was also chosen to provide a simple turbine design, as well as variable speed control to reduce aerodynamic noise and to produce the maximum amount of energy. The Bonus 450 MkII has a design which is common in Danish wind power units. It has three blades, stall control, a rigid hub and a fixed speed.

Comparisons with other machines in the same size show that the NWP 400 is considerably lighter. The total weight of NWP 400 is 29 tons, including tower. The same figure for the Bonus 450 MkII is 42 tons. Another way of comparing the machines is to calculate the tower head mass divided by the swept area. Comparisons of the different mass figures show that the NWP 400 is 30-37% lighter than the Bonus 450 MkII.

Light wind turbines will in the future result in lower manufacturing costs and thus a lower cost per produced kWh. This requires that the concept fulfils the requirement on high availability. The purpose of this project is to investigate and verify this technique. Another prerequisit for the choice of design solutions was that it should be possible to scale them to bigger sizes.

Both units were started-up in 1992. The Bonus 450 MkII has since been in continuous operation with a high degree of availability and with normal faults for this type of unit. The control system has been adjusted so that it is better adapted to the wind conditions on the west coast, where the wind is more turbulent than at typical Danish sites for wind power stations.

The NWP 400 required a number of adjustments and modifications before it was taken over by Vattenfall and brought into normal production in 1995. However, even in the period before this take-over the unit was in operation for the major part of the time and measurement and evaluation of the unit was started in 1992. An early addition was an extra filter in the electrical frequency conversion system which is used to make variable speed operation possible. The power electronics generated harmonics which disturbed the Bonus 450 MkII. These harmonic disruptions disappeared once the filter was installed.

In 1993, one of the blades was damaged when it struck the tower. It was discovered that the blade deflection became too great at high wind speeds so that the blades could strike the tower under certain operating conditions. Some modifications were made in order to reduce these movements. In addition, the unit is stopped in the event of large teeter angles. This has led to a certain loss of production (see also below).

The units have been evaluated in line with a comprehensive programme. Production capacity, operating experience, how the units work together with the grid, and their impacts on the surroundings have been investigated for both units. In the case of the NWP 400, production capacity, aerodynamics, loads during operation and reliability in terms of fatigue have also been analysed. Co-operation with staff from the Swedish wind energy research programme has been valuable in this work.

In order to be able to carry out the planned evaluation of the units, they were equipped with a measurement system for the continuous registration of wind and production data. The NWP 400 was also equipped with gauges for strains, movements and other data which define the operating status of the unit. The measurement system has unfortunately been affected by some problems which have limited the possibilities to perform a long-term follow-up of a number of factors. Modifications have also subsequently been made to the NWP 400, which means that it has only been possible to carry out correct comparative studies of the two units for a limited time towards the end of the evaluation period. However, a great deal of data has been registered for different types of situations, data which will be of great value in analysing the unit and verifying the calculation models used. A lot of this material will also be of value in the continued research and development work of the Wind Power Consortium on the "Swedish line" with light and flexible units.

0.3 PRODUCTION RESULTS AND OPERATING EXPERIENCE

The Bonus 450 MkII has been in operation with minor disruptions since it was started-up in June 1992. During the first three years up to and including June 1995 it produced 2 893 MWh, which means that it did not achieve the expected average annual production. Operation was initially disrupted because the control system was sensitive to turbulent wind, so that the unit was not engaged when wind conditions were unstable, and also because harmonics in the network disturbed the control system. These disruptions ceased when the control system was adjusted and a harmonics filter was installed in the NWP 400.

The NWP 400 is a development unit for testing new technical solutions. It is therefore natural that there have been some technical problems and operational disruptions, and that modifications and adjustments have been required. Some problems remain, and these disrupt operations and prevent the unit from achieving the desired production result. Since start-up on 15 September 1992 the unit has produced 1 060 Mwh, till June 1995.

For a large part of the period, operation was partly limited due to alignment work, adjustments, or to operating restrictions while awaiting repairs or modifications. Even today, June 1995, the unit is not meeting expected production levels as it is turned off for safety reasons when the movements in the teetered hub become too great.

Given this background, an accurate analysis of the production and operation of the two units was only possible in the later part of the evaluation period, i.e. during the 12-months from June 1994 to May 1995.

The following production figures were achieved during this period:

Production 450 MkII	1092.3 MWh
Mean production when connected to network	177 kW
Mean production per calendar time	125 kW
Availability	93%
Production NWP 400	696.5 MWh
Mean production when connected to network	132 kW
Mean production per calendar time	80 kW
Availability	82%

The lower production figure for the NWP 400 is explained by the operating problems mentioned above. A closer analysis of the availability statistics shows that 532 hours (6.1%) were lost as a result of too great teeter angle. In addition, 138 (7.6%) hours were lost due to high wind (the stop limit has been downrated). This corresponds to a fall in production from 1 016 MWh to 850 MWh. The remaining unavailability time amounted to 1 100 hours, which in total gives an availability figure of 87%. This reduces production to 740 MWh. The remainder is explained by uncertainties in the wind-power curve.

The relatively low availability of Bonus 450 MkII in comparison with other commercial units is mainly due to problems with the control system, stoppages in connection with over-production and problems with oil transmission to the hub. If these causes of disruption are discounted, we are left with an availability figure of 98%.

0.4 TECHNICAL EVALUATION

Basic demands on a wind power station are that it should produce as much power as possible from the available wind at as low a cost as possible, that it should be designed so that it presents no danger to its surroundings and can cope with the varying loads it is subjected to, that it should not cause disturbances in the power network, and that it should have a control system which can handle the different situations that arise. The aim of the technical part of the evaluation programme was primarily to investigate how well the new technical solutions used in NWP 400 work. In the case of the Danish unit, the technical evaluation was limited to measuring production capacity, noise and how well the unit co-operates with the power network, as a part of the general comparison between the two units.

0.4.1 Production capacity

Production capacity, i.e. a unit's ability to produce energy from the wind, can be expressed in several ways: as a wind-power curve which shows the output at different wind speeds, as an estimated annual production given specified wind conditions, or as an estimated mean output during the year. For detailed comparisons of two units, the efficiency of the turbines can also be expressed in so-called Cp-λ curves. The latter presupposes, however, that the mechanical moment of the rotating system can be measured in a satisfactory way, which is difficult in the case of the NWP 400 due to its design.

The production capacity of both of the units was investigated on the basis of measurements of wind speed and output during the period October - December 1994. Wind-power curves were determined from the measurement data in accordance with a standardised IEA method, and annual production and mean production were calculated on the basis of these curves. The reason that so short a time was chosen for the comparison was the ambition to achieve a fair comparison over a period in which both of the units were exposed to the same wind conditions and were in operation all the time, and in which no modifications were made.

The estimated annual production for NWP 400 as it was operated during the follow-up period (wind interval 4.25 to 15.75 m/s), and provided that no disruptions in operations occur, is 1 030 MWh. The mean power output of the unit is 118 kW calculated over all the hours of the year. The wind is assumed to have an average speed of 7.5 m/s and to be Rayleigh distributed. The level of uncertainty in estimated annual production is $\pm$ 85 MWh, while for power it is $\pm$ 10 kW.

Estimated annual production according to the supply contract is 1 096 MWh. During the period, the unit was stopped at wind speeds of 15.75 m/s or more instead of at the intended 23 m/s, in order to reduce the risk of the blades striking the tower in the event of large movements in the teeter hub. With this limitation, annual production in accordance with the contract would be 1 003 MWh. Given these conditions, the unit has produced more power than expected.

The estimated annual production for Bonus 450 MkII is 1160 $\pm$ 95 MWh, and mean production 132 $\pm$ 11 kW. According to the contract, annual production should be 1 227 MWh.

At wind speeds under 6 m/s, NWP 400 performs better than Bonus 450 MkII. This is explained by the better system efficiency achieved with variable speed operation.

The conclusion of the study of production capacity is that the measurements confirm that the units reach the expected production levels. The measurements are, however, subject to some degree of uncertainty, as the period in which both units were in operation at the same time without being modified was relatively short.

0.4.2 Loads, stresses, fatigue

An important part of the evaluation of NWP 400 was to investigate whether the unit, with its new technical features, worked as expected from the calculations on which the design was based. Bonus 450 Mk II is a series-manufactured unit designed in accordance with values gained from previous experience, and it has therefore not been a part of the evaluation to carry out such a study for Bonus 450 MkII.

In order to be able to measure loads and deflections, NWP 400 was equipped with gauges for forces, moments and accelerations in the blades, machinery housing and tower. The measured values were registered together with data on the wind and on the operation of the unit in order to provide a basis for calculations of inherent frequency, loads, stresses, resistance to fatigue and so on. The measured inherent frequencies for the blades and tower closely correspond to the estimated values. Neither known connections between oscillation modes or other inherent frequencies are expected to give rise to any problems for the unit. Calculated loads and movements for the unit lie well within the expected range. The wind conditions actually measured were no more severe than the wind figures used in the design calculations. The assessment is that the unit meets the requirements set for safety with regard to fatigue.

Special attention was paid to analysing conditions in connection with yawing and to investigating the dynamics in the teeter hub. An important part of the design of NWP 400 is the combination of stall control, teeter hub and yaw dynamics with variable speed operation. The damping and absorber features in the yaw system performed to expectations. However, yaw control did not function as well as intended, which may have contributed to the large teeter movements which occurred in connection with high winds.

As mentioned above, a blade was damaged in 1993 when it struck the tower in connection with major teeter movements. In order to reduce the blade deflections, several modifications were introduced, including stopping the unit in the event of large teeter angles. Analyses of the problem indicated different ways of further reducing the teeter movements, and thus the extent of the consequent stoppages. Experience from this evaluation was of great value in the design of the larger unit, NWP 1000 (1000kW), which was started-up at Näsudden in the summer of 1995.

0.4.3 Co-operation with the grid

Production from a wind power station can vary quickly due to wind speed. A requirement concerning such stations is that these variations must not lead to unacceptable disturbances in the power network, and that connection and disconnection must only lead to small variations in voltage and current. Measurements of current and voltage were mainly carried out at the point of connection to the network which is common to the two units. These measurements were carried out in accordance with the recommendations of the IEA.

Measurements revealed that the units had little effect on the network during operation, and connection caused acceptable disturbances. The largest voltage drop, 3%, occurred when connecting the Bonus 450 MkII.

The power electronics, which convert the variable frequency from NWP 400 to the frequency of the network, caused harmonics in the current and voltage to the network. Special attention was devoted to this problem. Two of the registered harmonics exceeded Vattenfall's internal recommendations for permitted harmonic content, though only by a limited amount. This occurred when NWP 400 was operating at low power and was of little significance to the network. However, the harmonics initially created a number of disturbances in the control system of the Bonus 450 MkII, which led to unwanted stoppages. These were not seen after the extra filter was installed in the NWP 400. Long-term monitoring of the occurrence of short voltage drops in the network revealed that this happened on a number of occasions, but the disturbances came from the network, not from the units.

0.4.4 Function of the control system

An evaluation of the functioning of the control system was originally part of the evaluation programme for NWP 400. The control system is a central part of the technical solution with variable speed operation, a teeter hub and stall control.

Unfortunately, this evaluation was delayed due to measurement difficulties.

However, operating experience and other studies show that the unit largely functions as intended, and that it can cope with the changes in wind conditions and disturbances in the network that occurred. The possible exception is the yaw control system, where analyses of the teeter movements indicate that this did not work as intended in connection with rapid changes in wind speed and wind direction.

0.4.5 Special tests

A number of special questions, primarily concerning aerodynamic properties and how these relate to unit dynamics and loads, were investigated in several measurements and trials for NWP 400. The questions investigated were the effect of different blade settings, the aerodynamic properties of the blades and the effect of stall strips.

A frequency analysis of the output in 1994 showed a disturbance with the same frequency as the turbine rotation. It was discovered that this was due to a difference in the adjustment of the blade angles (-2.2° and -1.7°). Adjusting both the blades to a smaller angle (0.8°) produced a smaller disturbance, but it also created a higher peak power and rapid, unwanted power peaks at high wind speeds. In order to correct this, new stall strips[2] were mounted which had the desired effect but which also reduced rated output more than intended. It is expected that continued adjustment will provide increased production as well as acceptable power peaks.

Unit-mounted gauges mounted on the unit for wind speed, wind direction and power have been examined and calibrated with the gauges of the measurement system. The wind direction gauge gave a signal with a high degree of uncertainty. It was possible to calibrate the other gauges to a degree of accuracy such that they could be used for measurements and evaluations.

[2] "Stall strips" is a mechanical device (small L-shape) mounted on the leading edge of a blade. It is used to limit maximum liftforce on parts of the blade

0.4.6 Wind measurements

Wind conditions at the site were investigated by measuring wind speed, wind direction and temperature at five levels up to an altitude of 65 m, using a special wind measurement mast located between the units. Humidity and air pressure were also measured on a continuous basis. The evaluation is based on measurements from June 1993 to March 1995. The signals were registered with the help of MIUU's own measurement system and were then transmitted to the central measurement system. The average wind speed at the height of the hub (50 m above sea level) was measured as 7.2 m/s. Corrected for a standard year this becomes 6.5 m/s.

The measurements revealed that the wind was less turbulent than expected for this site, which is surrounded by islands and rocky terrain. The wind from the sea was approximately equivalent to the wind that could be expected over a flat, grass plain, while the wind from the land was comparable to that from a normal agricultural landscape with hedges, occasional buildings and villages.

A calculation of the average wind speed at Lyse compared to that at Måseskär, an open-sea site, shows that the wind speed at Lyse is 9% lower at a height of 65 m and 21% lower at a height of 25 m.

It must be pointed out, however, that from certain directions short-lived wind conditions with a high degree of turbulence and sudden shifts of wind were recorded.

0.5 IMPACT ON THE SURROUNDINGS

Wind power stations primarily affect the surrounding environment through the noise generated by the blades and machinery and through the fact that they change the landscape. They can sometimes also disrupt the transmission of electromagnetic waves such as television, radio and radar signals. These issues have been thoroughly investigated earlier in connection with Swedish prototype units, e.g. Maglarp and Näsudden I. At Lyse Wind Power Station, measurements were caried out to determine the extent of these disruptions in the surrounding area, and to establish how the Wind Power Station was regarded by the local residents.

No impact on bird-life was reported, but birds damaged the meteorologists' wind speed gauge on several occasions.

0.5.1 Noise

The Wind Power Station generates noise partly in the form of aerodynamic noise from the turbine blades, which move through the air at great speed, and partly in the form of mechanical noise from the machinery, where gears, generators, fans and pumps can all create noise.

The noise from the units was measured in noise emission measurements with each of the units running independently. These measurements revealed that the total noise emitted is somewhat higher for NWP 400 than for the Bonus 450 MkII, due to louder mechanical noise. At 8 m/s the sound pressure level is 2 dB (A) higher from NWP 400. The difference does not depend on the principal design of the NWP 400 and it should be possible to decrease the sound pressure level in a series production machine.

The noise actually perceived at different sites was also measured and compared to the expected values for three sites at a distance of 400 to 500 metres from the unit. These measurements showed that the acoustic pressure levels were low and corresponded well to the estimated values.

0.5.2 Impact on television reception

Measurements of television signal disturbances were carried out at nearby built-up areas. The measured values and picture quality at these locations were not affected by the wind power plants. Close to the units, at a distance of 100 to 300 metres, there were strong to moderate disturbances of picture and sound, and these were strongest when the signal passed the towers and turbines. People do not reside permanently in this area.

0.5.3 Attitudes to wind power on the part of local residents

Interviews were conducted with 20 year-round residents from Skalhamn and 24 summer residents in Ramsvik. The distance from the interviewees homes to the Power Station varied from 300 to 4 000 metres. There was also a reference group made up of people from the Municipality of Lysekil.

It is clear that Lyse Wind Power Station has helped to increase interest in wind power in the Municipality of Lysekil. In Ramsvik there is a greater degree of doubt about the development of wind power in what is the residents' holiday environment. It should be possible to remove this doubt through clearer production reporting. This would give a possibility to show the benefit of wind power. Another, requested, way would be to deliver the electricity directly to those living close to the wind power plant, if this was feasible.

All of the groups interviewed stressed that wind power plants should be located in suitable areas where they will not be seen as a disturbance. Certain sensitive areas must be left untouched. It is important to find sites for wind power plants in consultation with the population affected. Small groups of wind power plants are conceivable, but not large group stations. The technology must be developed so that the wind power plants really work and produce energy.

Noise disturbance was reported from Ramvik, although no link was established between the living distance from the station and the disturbance. Reflexes from surrounding rocks and cliffs may play an important role in how the noise is perceived. There is a correlation between reports of noise disturbance and a doubtful attitude to wind power development in the immediate vicinity of the home.

A clear majority of those interviewed said that they had a positive attitude to wind power as an environment-friendly and supplementary source of energy. It is important to inform people about what is required of areas considered for wind energy production, and where these areas are. It is also important to tell people why a Swedish development plant has been located next to a well tried and tested Danish wind power station. Co-operation with the tourist office in Lysekil should be developed further and the information building kept open longer. Wind power should be presented as a complement to other forms of power, and the current economic situation for wind power should also be presented. Assessments of usefulness have strongly characterised the views and experience of the resident population. Some of the preferences concerning the design of power stations are clearly linked to the amount of time different stations are prevented from operating. It is clear, however, that most people prefer turbines with three blades in this survey. Aircraft warning signals were not mentioned as a disturbing factor. Vattenfall is perceived as a serious and responsible company and it was felt that both the co-operation with the municipality and the information activities worked well for the most part.

0.6 CONCLUSIONS

The concept works, but some modifications are necessary

The main aim of the project was to test and evaluate a new wind power technique, partly through detailed measurements of the NWP 400 and partly through comparisons with the Danish standard unit. At the same time, it was a demand that the two units of the Power Station could be run as a production plant once the evaluation was complete.

The overall conclusion from operation, and from the various measurements and studies carried out, is that the new technique functions as intended and that the calculations and estimates made in connection with design work were largely correct. The evaluation confirms that the unit can meet expected production levels, that it can cope with different operating situations and that it can be expected to meet the demands set for loads and safety with regard to fatigue. The basic solutions have since been used in the new, larger unit, NWP 1000, which has been erected by Vattenfall at Näsudden on Gotland.

The evaluation has also shown that the calculation tools used to design the unit and calculate the production capacity have given correct results and good estimates.

Certain sub-systems did not, however, function as intended and modifications were required. Additional modifications may be required in a series production of NWP 400. In its present form the unit has difficulties at high wind speeds due to large teeter movements. According to calculations, it should be possible to further reduce these teeter movements and thus increase the availability.

The comparison between the units shows that both of the units have largely achieved the expected production capacity. As one of the units is a standard unit and the other a development unit and the first of its type, it is not possible to draw any far reaching conclusions on the differences in production capacity, availability and cost. The NWP 400 suffered more stoppages, transmitted some more harmonics to the network and is slightly noisier, but the evaluation indicates no obstacles to the correction of these shortcomings in a later version.

1. LYSE WIND POWER STATION

1.1 THE PROJECT

1.1.1 Background

Vattenfall AB has participated in the development of wind power since 1976. For many years wind power activities in Sweden were almost entirely directed towards the development of large wind turbines. This work continues with the development of Näsudden II, currently being evaluated under the EU-WEGA II program.

Another and new development line was initiated some years ago with the aim to find a design with low weight, uncomplicated design and cost effective power control.

In August 1990 Vattenfall decided to erect two wind turbines in the 400 kW- 500 kW range. One prototype, using the concept described above and one conventional wind turbine. This should allow for direct comparison between the two wind turbines.

1.1.2 Purpose of the project

The purpose of the project is to develop and test new technical solutions in order to reduce the cost of electricity produced by wind energy.

Experience from the Swedish wind energy programme was used during the design of the Swedish prototype, called Nordic 400, as well as during the evaluation of the project.

The project also includes an evaluation program. The objectives of the evaluation were as follows:

- to measure production results and gain operating experience
- to verify calculations, loads and dynamics of the Swedish prototype
- to produce basic data, through measurements and comparisons, for further development of the Swedish wind energy program
- to investigate the environmental impact from the wind turbines
- to determine the conditions, by continuos wind measurements, for a typical location at the Swedish west coast

The evaluation program is in detail described in [1]. In this program the overall goal for the fulfilment of the evaluation was described. During the work a number of modifications were made to the original program. The evaluation of the performance of the control system and drive train was not so extensive as anticipated due to problems with the data acquisition system. Some additions to the evaluation program were also made in order to study interesting phenomena. An example was the increased evaluation of aerodynamic properties of NWP. Alterations to the original program are mentioned more in detail in Chapter 3.

1.1.3 Project management

The project has been conducted by Göran Dalén at Vattenfall in Stockholm.

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[1] Program för utvärderingen av Lyse vindkraftstation, Slutgiltig version 1992-06-05

Lyse Wind Power Station is operated and supervised by Vattenfall's local office in Trollhättan, located approximately 70 km east of the site. Maintenance personnel are located in Uddevalla, approximately one hours drive by car and ferry from Lyse.

The evaluation of the project was supervised by Pär Svensson, Vattenfall, and from October 1994 by S-E Thor, FFA.

1.1.4 Time schedule

1990	
August	The project started.
October	Contract with Nordic Wind Power regarding the design of Nordic 400.
1991	
November	Building permit given for the project.
December	Contract with Nordic Wind Power regarding the delivery of Nordic 400.
December	Contract with Bonus Energy A/S regarding the delivery of one Bonus 450 kW Mk II wind turbine.
1992	
February	Contract with Vattenfall Utveckling AB regarding development and delivery of a Data Acquisition System for the Nordic 400 wind turbine.
May	Foundations and information building completed.
June	Bonus 450 MkII wind turbine installed and connected to the grid.
August	Nordic 400 installed and connected to the grid.
August	Meteorological tower instrumented and data acquisition system on Nordic 400 installed.
September	Inauguration of Lyse Wind Power Station.
October	Start of evaluation.
1995	
June	End of evaluation
September	Presentation of evaluation

1.1.5 Financing

The total budget for the project was 34.5 million Swedish crowns. Vattenfall was providing 50 % . NUTEK (Swedish National Board for Industrial and Technical Development) and Elforsk AB were providing 25 % each.

1.2 THE SITE

The site is located on the west coast of Sweden 80 km north of Göteborg, at a small land-fill, shaped as a peninsula, called Basteviksholmarna. The area around the site is rather heterogeneous, with an archipelago of rocky islands reaching typically 30 m to 50 m above sea level. The nearby mainland is nonhomogeneous with many rocky parts with peaks and plateaus up to about 50 m in height.

The site was chosen for many different reasons:

- the wind potential along the Swedish west coast is very good, but not yet utilized,
- the coastline is very rough representing complex terrain,
- the west coast is a popular resort area which may have impact on the acceptance of wind energy,
- the site gives very good opportunities for a direct comparison between new and well proven techniques.

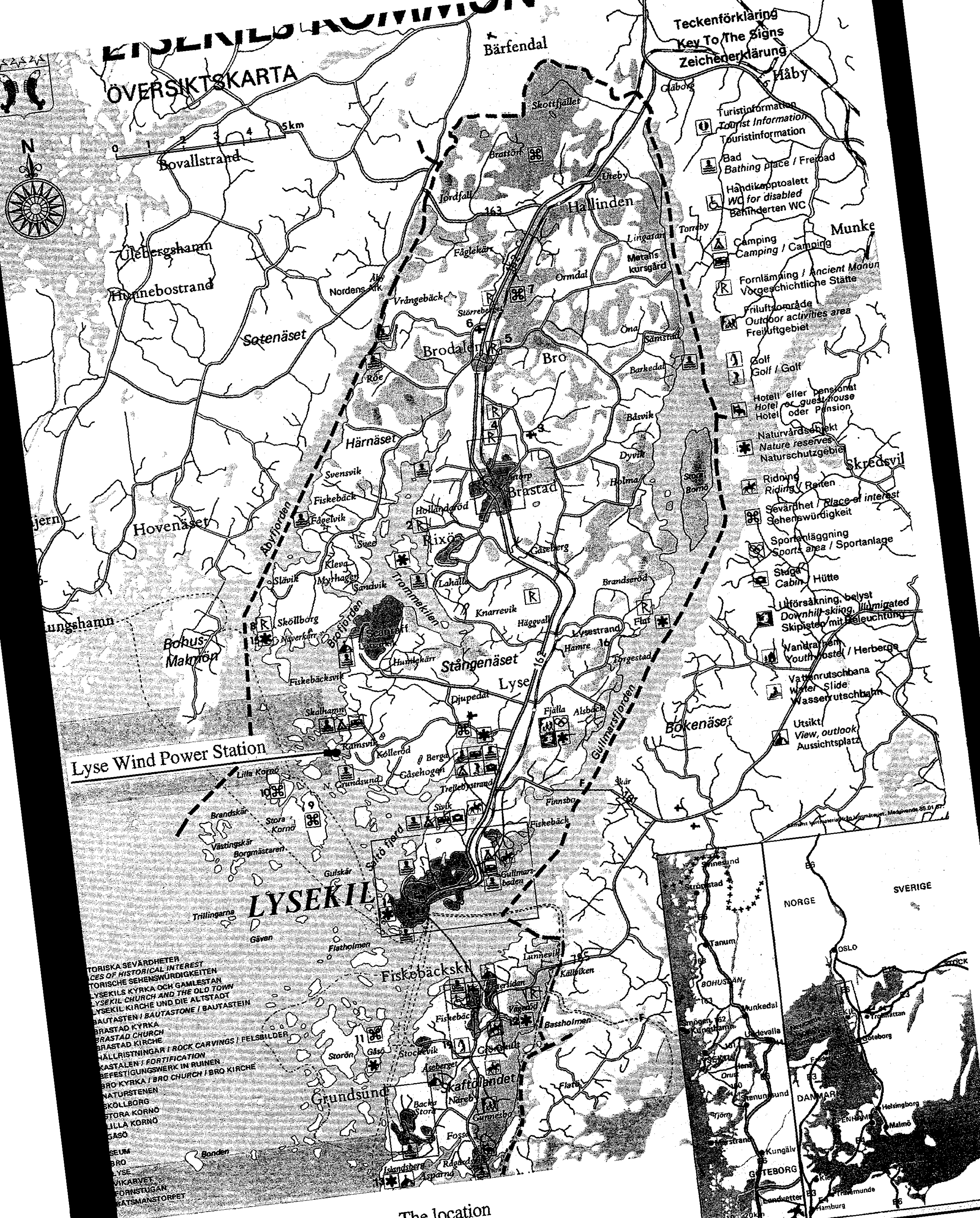


FIGURE 1.2:1 The location

1.2.1 PERMITS AND PUBLIC INVOLVEMENT

The west coast of Sweden is a recreational area of big importance. The coastline is rough and no trees are growing close to the water in this area. This means that the wind turbines will be visible at long distances.

Summer guests are normally more protective and conservative then people living all year around concerning local changes in the landscape. This was also true for this area. The people living close by were invited to an information meeting early in the project. A number of "information letters" were also sent to the people living in the area with information about the progress and purpose with the project.

The most common questions were:

- why here?
- will it be noisy?
- what will happen after the "tests are completed"?

It was decided at an early stage to minimise the damage on the environment. No access roads were built to the foundations of the machines.

The Swedish military have several installations along the coast which required that a thorough investigation had to be made before it was possible to get a building permit.

There were several projects intended for this site before the wind project started. Some serious plans with a tourist complex with hotel, restaurants and a harbour were stopped as a result of the local people protests to the Swedish Government.

None of the proposed project led to a permanent use of the islets. A small fishing industry existed for some years but was closed. People living in the neighbourhood and on the islands further out in the archipelago used the harbour for their private boats. But it was never developed as an "official" harbour.

The land was owned by the Community of Lysekil. Properties surrounding the wind turbines and the information building has been leased by Vattenfall AB for 25 years.

In general, no houses or other new installations are approved closer to 200 meters from the shore line. The county administration (Länstyrelsen) can however give exemptions to this, if required.

The work with the building permit started in the autumn of 1990.

A new "Detailed plan" for the area was presented in the summer of 1991 and approved later on in the autumn. Building permit and exemption regarding the "shore-close" regulations were given.

The co-operation with Lysekil Community has been very fruitful and gained the projekt.

The military approved the installation but required painted blade tips on the wind turbines, red light on top of the meteorological tower, and red light plus yellow flushing light on top of the nacelle. In order to draw good conclusions for the future, it was agreed to try different solutions for the two wind turbines.

The mean wind speed at the site was measured to 6.9 m/s when the project was planned. This figure was corrected to a annual mean wind speed of 7.1 m/s.

1.2.2 FOUNDATION AND LIGHTNING PROTECTION

The ground in this area consists of solid rock. It was the intention to minimise the impact on nature and there for it was not acceptable to remove rock by blasting or by the use of explosives. As little as possible should be visible in the future after a decommissioning of the wind turbines.

It was very clear that cracks in the rock do exist. These cracks are from the last ice-period about 10 000 years ago and can be seen in the northeast-southwest direction and perpendicular to this direction. A careful investigation was performed to avoid these cracks.

The design chosen is a concrete foundation, located on the rock and secured to the rock by 12 prestressed bars. These bars are about 10 meters long, diameter 36 mm and prestressed to 600 kN each. It is important to avoid corrosion in these steelbars and a double corrosion protection was used.

The diameter of the foundation for the Nordic 400 is 3,4 meters and for the Bonus 450 MkII 4,6 metres due to the larger tower diameter of the Bonus 450 MkII wind turbine. The smaller diameter for the Nordic 400 foundation did result in less material. But the securing steelbars, however, had to be installed with an inclination of 10 degrees in order spread out the forces. This led to a complicated drilling operation. There was no big difference in cost between the two foundations.

Lightning protection of a wind turbine, located on a rock is difficult to achieve by normal means. The distance to the open sea in this case was also too long (> 50 m). The transformer, located between the two wind turbines, is earth connected by the normal grid and also by copper lines running out into the open sea.

In conjunction to each wind turbine, a hole was drilled with the aim to find salt sea water. Astonishing, no sea water was found, not even after 50 meters depth. The hole was "hydraulically cracked" and fresh water is now available. A copper line is attached to the tower and fed down into the hole. How good this system is in case of lightning is difficult to say. No lightning damage has been observed on the Nordic 400. I should be noted that the meteorological mast, located aprox. 80 meters from the Nordic 400 wind turbine may work as a "lightning shield".

1.2.3 AIRCRAFT WARNING LIGHT

The military required air craft warning lights on the wind turbines. The area is used by the Swedish Air Force for training down to 50 meters above the sea level. In order to decrease the costs for this kind of warning systems it was agreed to try something different on one of the wind turbines.

The standard wind turbine (Bonus) was equipped with the normal system, i e red blade tips (Figure 1.3:2), red stationary and yellow flashing lights on top of the nacelle.

The Nordic wind turbine was equipped with normal white blade tips (Figure 1.3:3) and with a new type of warning light. The new type was a stroboscopic lamp with yellow glass and flashing at a frequency of about 1 Hz. The lamp was mounted on a steel plate in order to shield the light below the horizon.

The meteorological mast was equipped with standard red lights (one in operation and one as a reserve).

Vattenfall received complains from people living in the neighbourhood regarding the warning light used on the Nordic wind turbine. The stroboscopic light was disturbing even though it was well shielded. Especially during cloudy and foggy days when the light was reflected against the sky. It was agreed to stop the use of the new type of warning light in January 1995.

The opinion among pilots regarding what system to use is not clear. Some prefer a system with stationary red and flashing yellow. Others prefer only painted blade tips.

The conclusion from this project and other installations have resulted in that the requirements today are normally only red stationary warning lights, located on top of the nacelle. No painted blade tips or flashing yellow light is required.

1.2.4 Site lay-out

The site consists of the two wind turbines, a meteorological tower and a visitors centre which also houses the measurement system.

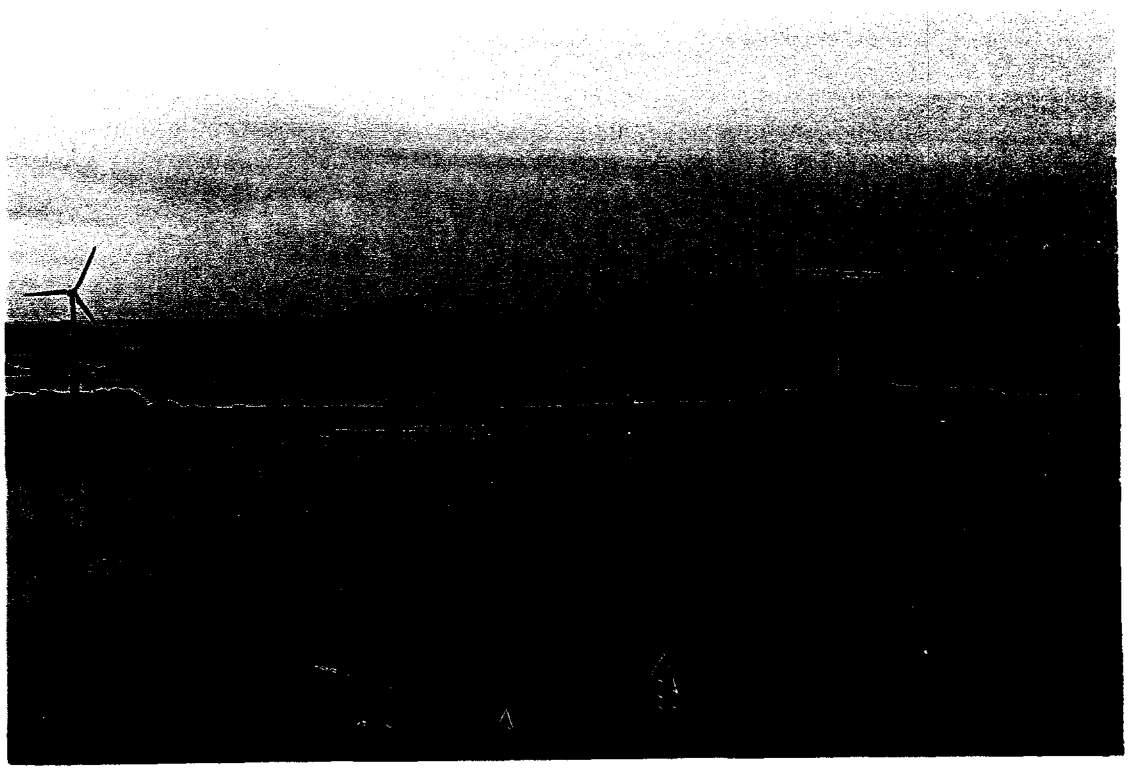


Figure 1.2:2 View of the site, looking west

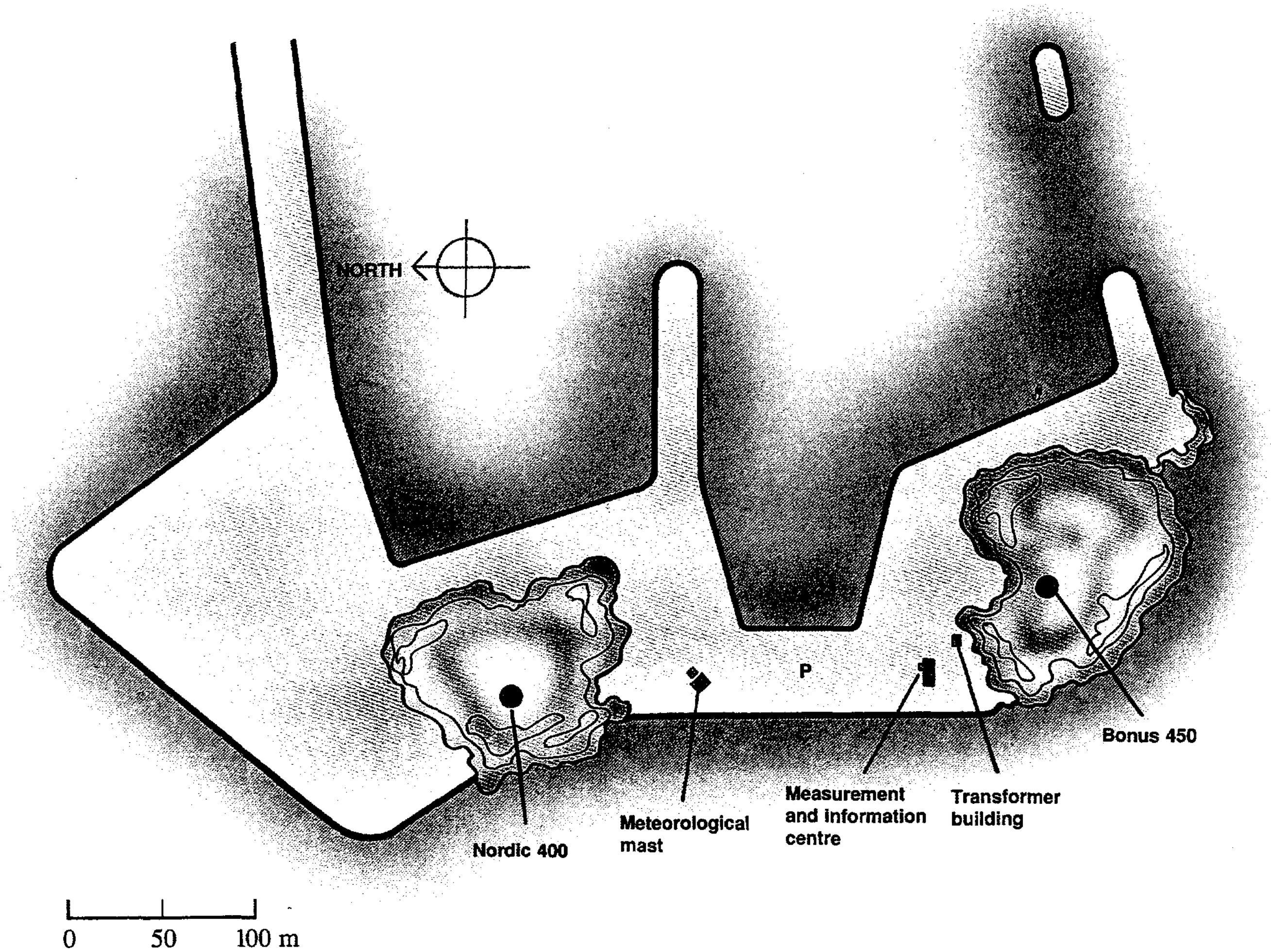


Figure 1.2:3 Map of the site

1.2.5 Meteorological Tower

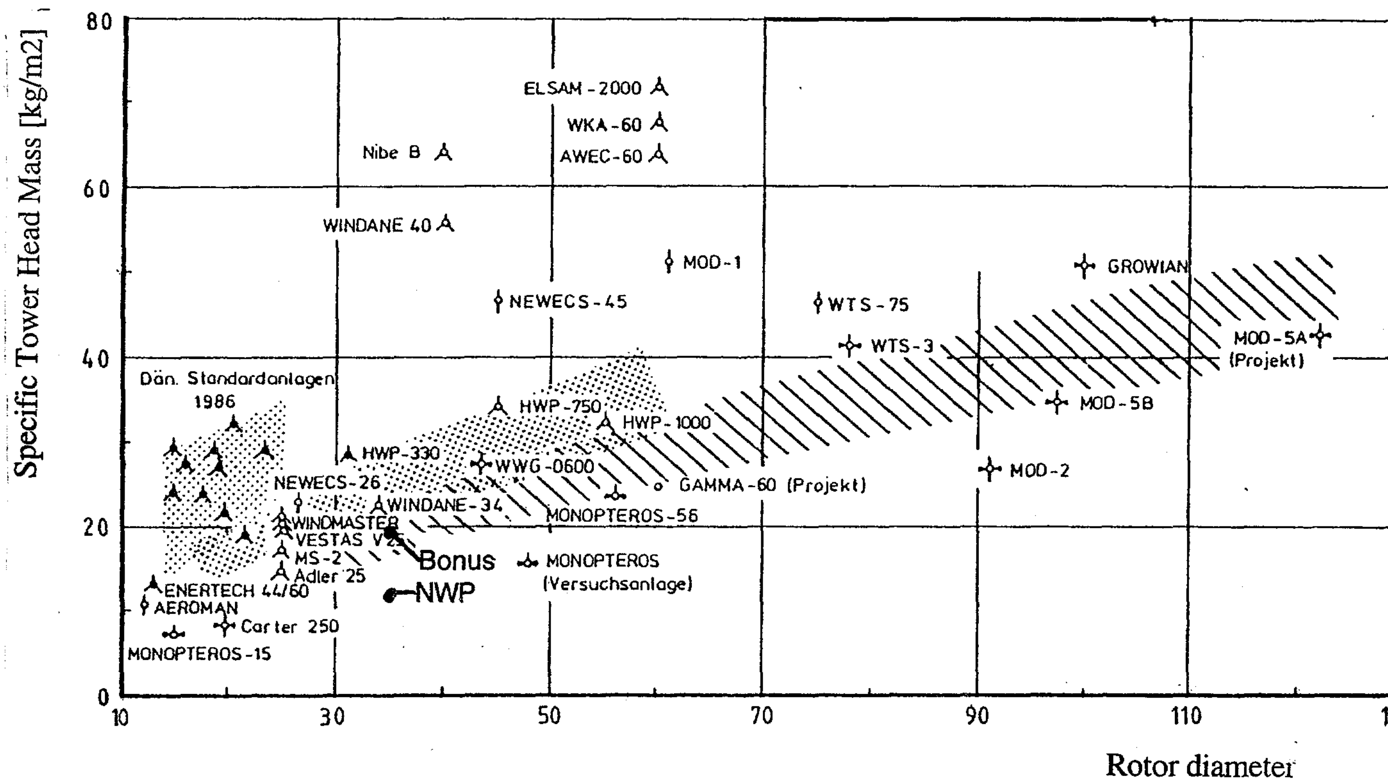
The meteorological tower is 66 m high with a square cross section. It was instrumented with combined cup/wind vane anemometers at 7 heights, giving information on mean wind conditions and turbulence characteristics of both longitudinal and lateral wind components.

1.3 THE WIND TURBINES

The main features of the turbines are given in the two sections below. The section describing the NWP 400 is somewhat longer since we wanted to give a detailed description of the rather unconventional concept. The general appearance of the two machines are shown in Figure 1.3:1

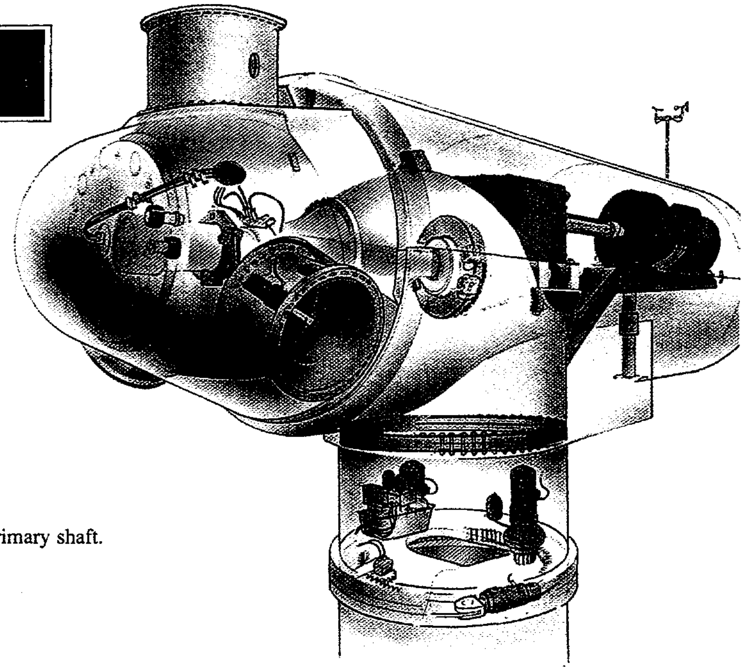
The basic philosophy in the design of NWP 400 was to minimise loads and stresses, partly by attaching the two-bladed turbine to the shaft with a teetered hub, and partly through a soft and damped connection between the machinery housing and the tower. Low loads makes it possible, in general, to reduce the total weight and thereby the manu-facturing costs of the unit. Stall control was also chosen to provide a simple turbine design, as well as variable speed control to reduce aerodynamic noise and to produce the maximum amount of energy. The Bonus 450 MkII has a design which is common in Danish wind power units. It has three blades, stall control, a rigid hub and a fixed speed.

Comparisons with other machines in the same size show that the NWP machine is considerably lighter. The total weight of NWP 400 is 29 tons. The same Figure for the Bonus 450 MkII is 42 tons. Another way of comparing the machines is to calculate the tower head mass, THM, divided by the swept area. Comparisons of the different mass Figures show that the NWP machine is 30-37% lighter than the Bonus 450 MkII.



Ref. Hau Windkraftanlagen

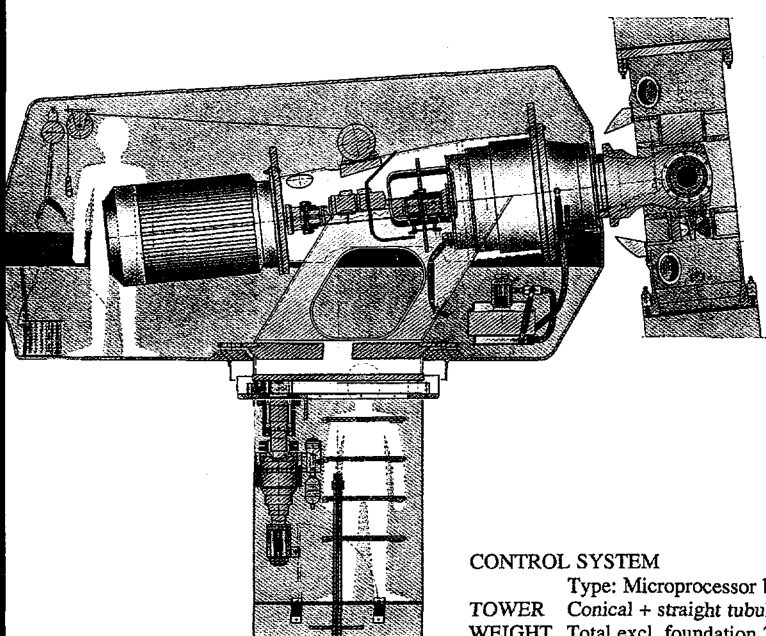
Bonus 450 kW Mk III



Supplier:	Bonus Energy A/S, Denmark
ROTOR	
Type:	Fixed hub
No. of blades:	3
Diameter:	36 m
Speed:	35 r/min.
Power regulation:	Stall

OPERATING DATA	
Starting wind:	5 m/sec
Rated power, reached at:	14 m/sec
Shutdown wind:	25 m/sec
TRANSMISSION SYSTEM	
Gearbox:	1-stage, planetary gearing 2+3 helical gear

GENERATOR	
Type:	Asynchronous generator
Output:	450 kW
Operating data:	50 Hz, 690 V, 1500 r/min.
BRAKING SYSTEM	
Air brakes:	Pivotable blade tips
Mech. brakes:	Hydraulically-activated disc brakes on the primary shaft.
CONTROL SYSTEM	
Type:	Microprocessor based
TOWER	
Conical tubular tower:	35 m hub height
WEIGHT	Total excluding foundation 46 tons.



Nordic 400

Supplier:	Nordic Windpower AB, Sweden	
ROTOR	Type:	Teetered hub
	No. of blades:	2
	Diameter:	35 m
	Speed:	Variable 20-41 r/min.
	Power regulation:	Stall
OPERATING DATA	Starting wind:	5 m/sec
	Rated power, reached at:	13 m/sec
	Shutdown wind:	25 m/sec
TRANSMISSION SYSTEM	Gearbox:	2-stage, planetary gearing
GENERATOR	Type:	Asynchronous generator
	Output:	400 kW
	Operating data:	50 Hz, 690 V, 1500 r/min.
BRAKING SYSTEM	Air brakes:	Pivotable blade tips
	Mech. brakes:	Hydraulically-activated disc brakes on the secondary shaft.

CONTROL SYSTEM
Type: Microprocessor based
TOWER *Conical + straight tubular tower: 40 m hub height*
WEIGHT Total excl. foundation 28 tons.

Figure 1.3:1 General view of Bonus and NWP wind turbines.

The main technical data for the turbines are as follows:

	BONUS 450 MkII	*NWP 400*
General		
Cut in/cut out (low)	5	4 m/s
Cut out (high)	25	23 m/s (10 min mean)
Cut in (high)		18 m/s
Extreme wind speed (2 s)		53 m/s
Extreme wind speed (10 min)		41 m/s
Fatigue life	25	30 years
Ambient temperature	-30°, +40° C	-30°, +40° C (in oper.)
Blades		
Material	GRP - polyester	GRP - polyester
Airfoils		NACA63.2xx/FFA-W3
Twist		12°
Root choord		1.85 m
Tip choord		0.4 m
Optimal tip-speed ratio		8
Air brake	Pivotable blade tips	Pivotable blade tips
Activation of air brake	Passive	Passive
Blade length	17	16,5 m
Manufacture	LM Glasfiber A/S	LM Glasfiber A/S
Turbine		
Number of blades	3	2
Power regulation	Stall	Stall
Turbine diameter	35,8	35,4 m
Swept area	1006	984 m^2
Cone angle	0	0°
Rotational speed	35	Variable 20-41 RPM
Maximum tip speed	66	75 m/s
Blade tip angle		-2°
Tilt		6°
Hub height	35	40 m
Nacelle		
Material	Steel	Glass fibre reinf. polye.
Dimensions		4,6x2,5x2,2 m
Load supporting parts of nacelle		
Hub type	Rigid	Teeter ± 7,5°
Teeter bearing	NA	Rubber
Teeter bumpers	NA	Rubber
Hub material	Nodular cast iron	Nodular iron
Main bearing	Spherical roller bearings	Spherical roller bearings integrated into gearbox
Gear-box		
Type	3-stage planetary/helical	2-stage planetary
Gear ratio	1:42,9	1:40
Output rpm	1500	800-1640 rpm
Lubrication	Splash	Splash
Cooling	Air	Separate oil cooler
Manufacture	Flender AG, Germany	Flender AG, Germany

Electrical system		
Type of generator	Asynchronous	4 pole induction
Rating	450	430 kW
Class	IP 54	IP 54, class F/B
Voltage	690	690 V
Cabling	Flexible cables	Flexible cables
Frequency converter	NA	SAMI, AC-DC-AC
Manufacture	ABB	ABB, Finland
Braking system		
Air brake	Turnable blade tips	Turnable blade tips
Activation/deactivation	Centrifugal/hydraulic	Centrifugal/hydraulic
Mechanical brake	Hydr. disc brake	Hydr. disc brake
Activation/deactivation	Hydraulic press. Active	Springs/hydraulic press. Passive
Yawing system		
Type	Electric motor	Electrical with hydr. damping
Yaw gear box	Helical/planetary	4 stage planetary
Ratio gear box		700
Ratio yaw drive		6
Motor		Induction with parking brake
Power		1,5 kW
Tower		
Type	Tapered tubular	Conical/cylindrical welded of steel plates
Height	35	38,5 m
Diameter top/bottom		1,3/1,9 m
Access	Inside ladder with falling protection	Inside ladder with falling protection
Protection	Painted	Painted
Control system		
Type	Microprocessor	Industrial-PC DX486-33 MHz with modem connection
Weights		
Rotor	6500	5400 kg
Nacelle excl. turbine	15000	8100 kg
Tower	20000	15000 kg
Total including tower	41500	28500 kg

1.3.1 Technical description of 450 MkII

The wind turbine - named Torborg (referring to the name of the day when it first was connected to the grid) - was delivered by Bonus in Denmark. The machine is of traditional Danish design with three blades and stall regulation.

The machine was approved by Risø Test Station and obtained a design verification by Det Norske Veritas. Below is an excerpt from Bonus description of the machine.

1.3.1.1 Blades

The blades are manufactured from glass fibre reinforced polyester, by LM Glasfiber A/S. The blades are of a design similar to LM 11 m blades used on the BONUS 150 kW turbine and by other wind turbine manufacturers.

The blade tips are pivotable and can be turned 90 degrees, thereby acting as aerodynamic brakes . The blade tip shaft is made of carbon fibre reinforced plastics. All other load supporting parts are made of high-strength stainless steel. The blade tips are actuated hydraulically from the hub, a hydraulic pressure is operating against a spring force to keep the tip in the operation position.

The blade root is made with special nuts embedded in the main spar of the blade.

Figure 1.3:2 Bonus blade tip
Note noise reduction arrangement on the tip

1.3.1.2 Rotor hub

The rotor hub is cast in nodular cast iron. The hub is mounted on a fixed shaft by the main bearings. The three hydraulic actuators for the blade tips are located inside the hub for easy maintenance. For derails see Figure 1.3:1.

1.3.1.3 Main shaft and bearings

The rotor hub acts as a bearing housing for the main bearings, and the inner races of the bearings are fitted to the fixed shaft which is bolted to the nacelle bedplate. The fixed shaft is hollow, and the torque is transferred from the rotor hub to the gearbox by a transmission shaft, rotating inside the fixed shaft. The connection between the rotor hub and transmission shaft is a large, elastic rubber coupling.

1.3.1.4 Gearbox

The gearbox is a custom-built three-stage planetary/helical construction. The first high torque stage is a planetary stage.

The intermediary and high speed stages are helical, giving a low noise level. The gearbox is splash lubricated and surface cooled, requiring an oil pump or pressurised oil system.

The gearbox is shaftmounted. The main shaft torque is transferred by a shrink disk connection. The gearbox is mounted onto the nacelle with flexible rubber bushings, thereby reducing structural noise transfer.

1.3.1.5 Mechanical brake system

The mechanical brake system consists of a hydraulic pump system, 4 brake callipers at the low speed shaft and 2 callipers at the high speed shaft of the gearbox. The brake system is a positive system. The brake is applied for maintenance purposes, emergency stop, power loss and over speed stop. The brake is designed to stop the turbine even if the blade tips are inactivated.

1.3.1.6 Generator

The generator is a 4-pole asynchronous induction generator - IP 54 - with an internal fan, fixed to the rotor shaft. The generator rotor construction and stator windings are specially designed for wind turbine operation.

1.3.1.7 Yaw system

The yaw system is a separate module inserted between the tower and nacelle bedplate. The yaw bearing is an internally geared slewring. The yawing is driven by an electric helical gear motor fitted to a two-stage planetary gearbox with splined-on pinion. The yaw brake is a large drum brake, actuated hydraulically with an hydraulic cylinder, keeping the yaw system rigid under most loading conditions. In case of high eccentric peak loads the yaw brake will slide and the yaw motor will follow the motion passively.

1.3.1.8 Tower

The machine has a tapered tubular steel tower. The tubular tower has internal ascent and direct access to the yaw system and nacelle.

1.3.1.9 Operation and safety systems

The turbine operates automatically. When the wind increases from low values the turbine will start at about 5-6 m/s average wind speed, by itself. This wind speed is sufficient to accelerate the rotor to the synchronous speed, and the turbine will connect to the grid with the thyristor cut-in module, shortly after to be by-passed by the main contactor in order to reduce the solid state losses.

The power increases roughly linearly with the wind speed until the wind reaches 14-15 m/s. Here, the power is limited by the stalling of the rotor. At higher wind speeds the average power is reduced somewhat.

If the wind speed exceeds 25 m/s as a 10 min average the turbine is shut down through deployment of the blade tips. The rotor is not arrested but is left idling, as this is preferable to the main bearings.

In case of errors the turbine is shut down through deployment of the blade tips. The blade tips form the main braking system, and give a smooth shut down without significant transients. The blade tips are hydraulically retracted and are deployed at the release of the hydraulic pressure. The release system is fail-safe and has several levels of redundancy. These include monitoring of the rotor speed, monitoring of the back-pressure from the blade tips, which increase with the square of the rotor speed, and as the final safety system bursting discs in the hydraulic system of the rotor hub. The bursting discs will rupture in case of overspeed. The oil spilled flows back through the main shaft and is collected in a container in the nacelle.

The turbine will shut down with the deployment of only two blade tips in all wind conditions.

1.3.2 Technical description of NWP 400

1.3.2.1 The principal ideas of the design

The NWP 400 (Nordic 400) was designed with the general goal to extract power out of the wind by utilising a design which is lighter and less complicated than traditional wind turbines. In this way it should be possible to compete with other wind turbines and with other energy sources.

The amount of construction material is proportional to the loads that have to be sustained, and thus these have to be minimised. Fatigue loads during normal operation are limited primarily by the design of the hub and the yawing system. The teetering hub is designed in a way to even out the impact of both the stochastic variations of the wind speed (turbulence) and the periodic variation (wind gradient).

The main task of the yawing system is to keep the turbine in the direction of the wind. It is designed in a way which provides a soft and damped connection between the nacelle and the tower. The intention is that it will enable elimination of the build-up of any load inducing oscillations in the wind turbine installation. In the same way the way of governing the rpm (variable at low wind speeds, fixed at stall conditions) shall provide a way to damp the variations in the driving torque that would otherwise be induced by the turbulence and wind gradient.

When the wind turbine is shut down at hurricane wind speeds (in the order of 50 m/s) the design will be subjected to extreme loads which are directly proportional to the area exposed to the wind. The choice of a turbine with just two narrow blades minimises these loads. Static dimensioning load cases also appear during other situations, e.g. over-speed at grid fault and at rapid changes of wind direction.

A wind turbine is a slender design. Blade, tower and other components can easily be brought to oscillating movements. In order to keep the loads down it has been necessary to carefully consider the natural frequencies of the separate components and also the damping in the yaw drive and the electric system. In order to give the wind turbine favourable dynamics, extensive simulations were conducted with a computer program (Vidyn) developed by Teknikgruppen AB.

The variablerpm electric system means better aerodynamic performance and a decreased noise level at low wind speeds, when the ambient noise is low and thus the sensitivity to disturbances is high. The efficiency is at maximum when the turbine is running at a constant ratio between rpm and wind velocity. The consequence is that a lower rpm at low wind speeds is beneficial for both energy production and noise abatement.

The design is certificated by Det Norske Veritas.

1.3.2.2 Blades

The two blades, designed especially for the NWP 400, are built of glass-fibre reinforced polyester. They are bolted to the hub via a number of steel fittings laminated into the blade root.

The blade tips can rotate relative to the inner parts of the blades and thus brake the turbine when needed. During operation they are retracted by means of hydraulic cylinders in the hub. Braking is performed by release of the hydraulic pressure, which due to the centrifugal force, make the tips move outwards and rotate at the same time.

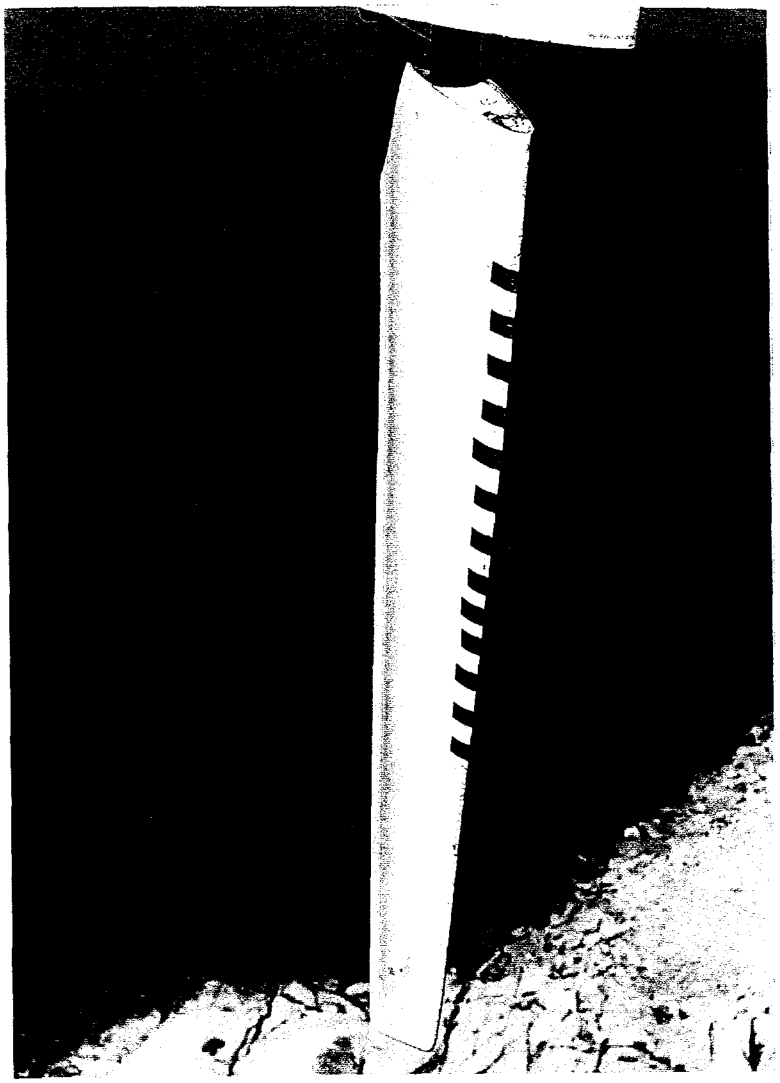


Figure 1.3:3 NWP blade tip.

1.3.2.3 Hub

The teetering hub consists of a cylinder with flanges for the blades and a fork, which is connected to the main shaft. The hub cylinder and the fork are connected to each other by rubber bearings. The teetering motion is counteracted by progressive rubber bumpers. The maximum teeter angle is 7,5 degrees in both directions. Both cylinder and fork are cast of nodular iron and designed for infinite life.

On the hub cylinder there is a hydraulic unit that serves the blade tips. Power supply is provided by slip rings also serving the measurement system. The blade tip cylinders inside the hub can be reached by man holes in the hub cylinder. The elliptical holes in the blade flange allow an adjustment of the angle of attack of the blades. The hub can be locked against any movement, used at e.g. maintenance.

1.3.2.4 Gear-box

The planetary gear-box increases the low rpm of the turbine to a value that is suitable for the generator. It also contains the main shaft bearings, which makes the wind turbine compact. The gear-box is flanged to the tubular machinery bed. The lubrication is of splash type, with cooling provided by a separate oil cooler. Temperature sensors indicate need for lube oil heating, cooling, shut-down of the plant due to high oil temperature.

1.3.2.5 Secondary shaft and mechanical brake

The secondary shaft carries the brake disc and two flexible couplings, one of them having a torque limiting capability. This Safe-set coupling is mounted between the generator and the brake disc, which means that the mechanical brake is serviceable also when the coupling is released. The two brake callipers utilise brake pads of a non-asbestos type. They are engaged by the force from springs when the hydraulic pressure is released (passive system). In the control system there is an indication for excessive wear of brake pads.

1.3.2.6 Machinery bed

The machinery bed is welded from cylindrical and conical sections. The gear-box is flanged to the front end of the bed, the generator to the aft section and downwards the bed is connected to the yaw bearing. Access for personnel is provided through the yaw bearing and a hole in the side of the bed. In order to avoid installation work in the nacelle most of the equipment is fixed to the machinery bed.

1.3.2.7 Nacelle

The nacelle provides a shelter for maintenance personnel and equipment, with full standing height .It is a self-supporting structure with no load carrying function for the machinery.

The nacelle is made of glass-fibre reinforced polyester in a top and a bottom half, which are bolted together. Inside there is sound insulating material on the walls and roof. The floor is covered with an anti-slip rubber mat. Intakes for ventilation air in the front of the nacelle are designed in a way that will suppress noise diffusion. The exhaust of the ventilation air passes through openings in the aft part of the nacelle, also designed for noise suppression, and through the oil cooler. The nacelle is fixed via vibration dampers.

There is a hoist on the top of the machinery bed that can be used to deliver equipment etc. through a hatch in the aft end of the nacelle or through the tower. It can also be used when lowering a blade tip to the ground. The hatch also serves as the emergency exit when using the evacuation equipment, in case of fire in the tower, etc.

On top of the nacelle there is a stand for wind velocity and direction sensors. They may be reached from a hatch in the roof. There is also a lightning conductor.

In the front end of the nacelle there is a large hatch that enables work on the hub. The weight of the hatch is balanced by gas cylinders.

1.3.2.8 Yawing system

The machinery bed and the tower top are connected by a yaw bearing, that enables the turbine to be positioned into the direction of the wind. The yaw drive consists of a geared induction motor with a parking brake. The rotation of the yaw drive is counteracted by a double acting hydraulic cylinder with hydraulic accumulators and damping orifices. During all operation - when yawing or not - the yawing system enables the turbine to perform small, damped movements.

1.3.2.9 Electric system

The electric system consists of an IP54 induction generator and a frequency conversion equipment that enables operation at low rpm at low wind speeds and at high rpm when the wind is strong.

The conversion equipment, which is of GTO-type (GTO=Gate Turn Off thyristor), is situated in a small building at the bottom of the tower. It consists of two identical frequency converters and a DC-link. The equipment is governed by a microprocessor which also communicates with the wind turbine controller. The generator converter produces a DC-current from the AC-current with varying frequency that is produced by the generator. It also produces the reactive power that is needed for magnetising the generator. In the grid converter 50 Hz AC is produced for the grid. Filters are used in order to reduce the harmonic content.

The converters are of an industrial standard type which are normally used to run motors at variable RPM. This capacity is used for starting the wind turbine. Then the generator works as a motor and accelerates the turbine to an RPM which is enough for the wind to drive the turbine. This function is also used for inching. All normal stops include inching the rotor to horizontal position, in order to avoid that one blade stops on the lee side of the tower, since this creates large asymmetrical forces on the rotor at extreme wind speeds.

The power is transferred from the generator through flexible cables that allow 1,5 rotations.

1.3.2.10 Tower

The conical-cylindrical tower is welded of steel plates. At top and bottom there are flanges for connection with the foundation and the yaw bearing respectively. The foundation is secured to the rock by 8 m prestressed steel rods.

Access to the tower is by means of a door on ground level and a vertical ladder inside the tower. Work platforms/protection against falling objects are arranged above ground level, at the inspection platform and just below the tower top.

The inspection platform is arranged like a drawbridge that can be extended from the tower wall at the height of the blade tips. It is made for inspections and work mainly on the blade tips.

1.3.2.11 Control system

The controller is based on an industrial type PC. It manages the complete operation of the wind turbine: surveys the systems when stationary, connects the electrical system at low rpm when the wind is strong enough, commands the wind turbine to follow the wind direction, "unwinds" the power cables when needed (by rotating the nacelle at stand-still), surveys all functions and stops the turbine when the wind becomes too strong or an emergency occurs. Access to the system is provided either directly at the base of the tower or through a modem and a local telephone line from the converter building or from the Vattenfall information building. Access to the system can also be provided through a modem and any PC connected to the general telephone network.

By means of a service box, that may be connected at the base of the tower or in the nacelle, the wind turbine may be yawed, inched or braked manually.

The wind turbine starts automatically when the wind is strong enough. Before the turbine is allowed to start rotation a number of pre-start controls are carried out. Once per month there is an additional control of the function of the blade tip brakes. This is done by deploying the brakes at a certain RPM with the controller checking that the braking power is as stipulated. During operation the RPM is adjusted according to wind speed in a way that the relation between the tip speed of the blades and the wind speed is constant = 8. This way of operation is maintained up to a wind speed of around 9 m/s. At higher wind speeds the RPM is kept constant, in order to limit the power by stall. At wind speeds exceeding 23 m/s (10 minute mean value) the turbine is stopped by increasing the braking torque of the generator. The mechanical brake is used as a parking brake. The turbine is restarted when the wind speed has decreased to less than 18 m/s.

If the braking power of the generator disappears, e.g. due to a grid disturbance, a fault in the electrical equipment or a release of the Safe-set coupling, the turbine may accelerate to dangerously high RPM's in a few seconds. Thus the system must be capable of braking the turbine in a safe way, with duplicated functions for indication and braking. A normal emergency stop is released by the controller after it has registered a faulty level of some parameter, e.g. grid voltage (grid loss), rpm, power, temperature, vibrations, etc. Through a "watch dog" function also a loss of the computer function activates an emergency stop.

The blade tips are activated by centrifugal force whereas the mechanical brake callipers are activated by mechanical springs. At grid failure the braking is already activated due to the loss of power. Either the two blade tips or one blade tip and the mechanical brake is enough to brake the turbine to a safe, low RPM. Thus the braking system is redundant.

As an ultimate safety feature there is a valve in the hydraulic unit in the hub that opens and drains the blade tip cylinders if the hydraulic pressure gets to high, thus indicating an over-speed condition.

1.4 DATA ACQUISITION SYSTEM

To carry out the evaluation program a measurement system based on a computer network was used. The main task for the measurement system was to store signals for strains, accelerations and power production (approximately 50 channels) at 32 Hz continuously for NWP 400. Only power production data from Bonus 450 MkII were measured. Meteorological data were stored at 4 Hz. Statistical values were stored in 1- and 10-minute intervals.

The data acquisition system (DAS) was delivered by Vattenfall Utveckling in Älvkarleby.

1.4.1 The system

Five PC-based computers with A/D-converters and signal conditioning were installed in the turbine. Data were collected through a computer network by a master PC which was responsible for synchronisation and file storage. Another PC was running as a server under Novell Netware. A third computer functioned as an evaluation PC with a tape-backup and a modem-connection, see Figure 1.4:1

The guiding philosophy was to keep the signal cables as short as possible to minimise disturbances from electrical noise. Therefore data collection was distributed into five nodes which were connected in a computer network. The measuring nodes were all powered by 230 V through an uninterrupted power supply (UPS).

The network server was equipped with a UPS for elimination of power disturbances and failures. The computer was a 486 DX 33 MHz PC with 12 MByte internal memory. It had a hard disk capacity of 1.2 GByte.

The Master or Mixing node was a 386-20 MHz PC with 1.5 MByte of EEPROM, 2 MByte internal memory and a programmable watch dog timer for rebooting. This PC gave the synchronising command and mixed the one second data-batches from each node into a common file. Every fourth hour the system was synchronised and a new data file was created. After midnight statistical values were calculated and all the files were stored on the tape backup unit.

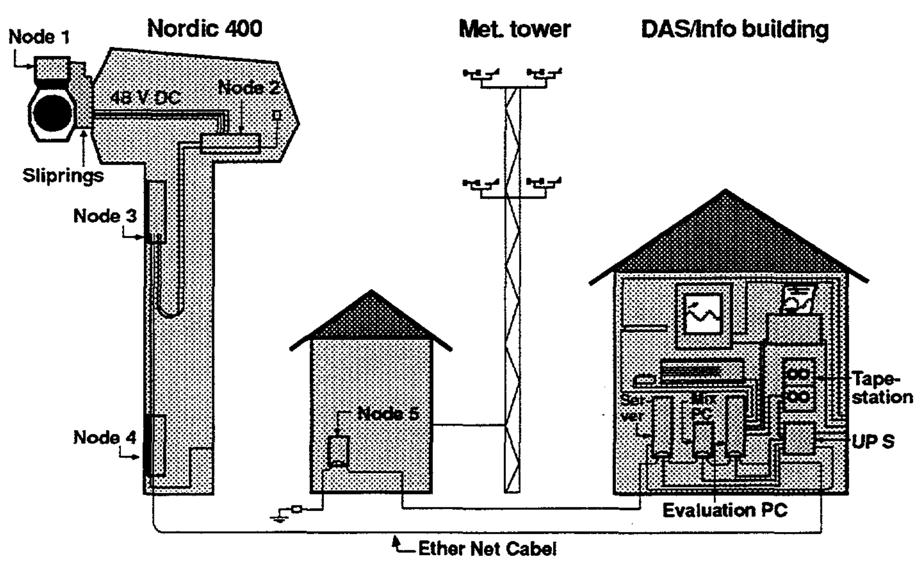


Figure 1.4:1: Data acquisition system overview

Four of the nodes were connected through a thick Ether-net cable. The fifth node was located in the hub and was connected to node 2 in the nacelle through two asynchronous two-wire modems connected to the sliprings.

Each node had one 286-16 MHz CPU-card with 1,5 MByte of EEPROM, a programmable watch dog timer and 2 MByte internal memory. The EEPROM contained the start-up files for the network communication.

Each node had been connected to earth in the part of the turbine were it was attached. All the nodes were connected through the Ether-net cable. The screens of all cables was connected to earth in both ends.

When a node had made its connections to the network it started to execute the measurement code. The Mix-node put the five one second files into a four-hour-file.

Each measurement node also had one AD-card and one network card. The AD-card, PC-lab card 812PG with a 12-bit AD-converter was capable of sampling 16 single ended channels at 30 kHz with programmable gain (1-16 times), 16 digital TTL channels and 1 analogue out channel.

Each channel was connected through lightning protection (3 stage). The lightning protection consists of a gas filled discharging pipe connected to a coil, a Zener diode and a coil again. Voltage peaks up to 10 000 Volt were hereby reduced to 35 Volt in order to protect the data acquisition system. Signal conditioning amplifiers for differential measurements were connected after the lightning protection. Antialiasing filters with cut off frequency set to 15 Hz were also used.

Transmission of data from the turbine was carried out by a pair of asynchronous modems and an RS232 connection. Every package of data (two second batches) was checked for missing values. Each sample was also checked. If a mismatch was discovered a pre-set value is inserted for each value or the whole batch of data. The transmission speed 19,600 bits/second did not allow any resending of erroneous data.

1.5 EXAMPLE OF MEASUREMENTS

The Figures below show results from measurements at different wind conditions.

Each plot represents 4 hours of operation. All plots therefore represents a time period of 12 hours. Each Figure consists of pairs of plots where the first one shows the meteorological conditions and the second one the production.

Legends first plot:

Thick line	represents wind speed [m/s], read value to the left
Thin line	represents wind direction [degrees], read value to the right

Legend second plot:

Thick line	represents produced energy [kW] by NWP
Thin line	represents produced energy [kW] by Bonus

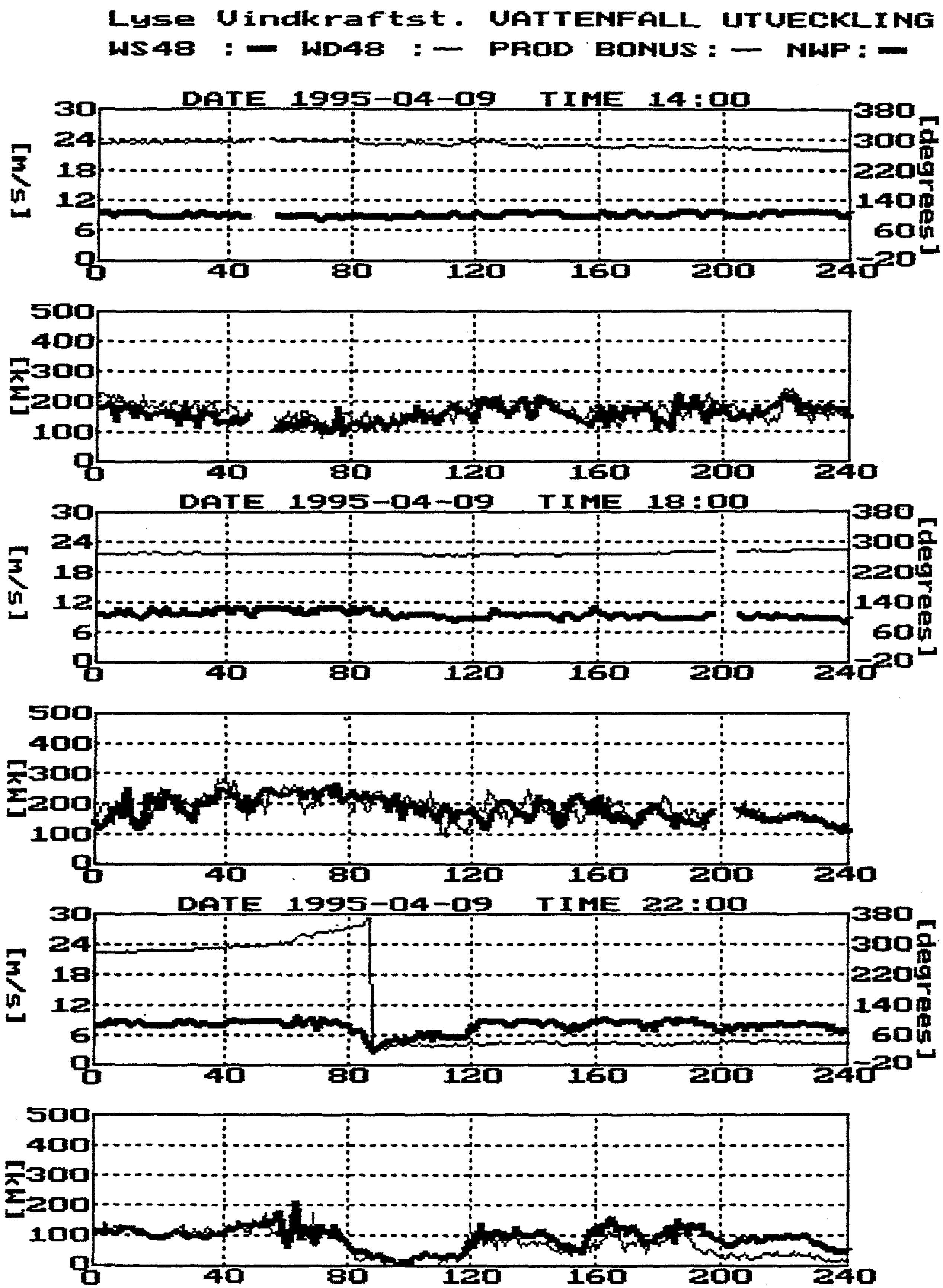


Figure 1.5:1 Low wind speed case, 9 April 1995

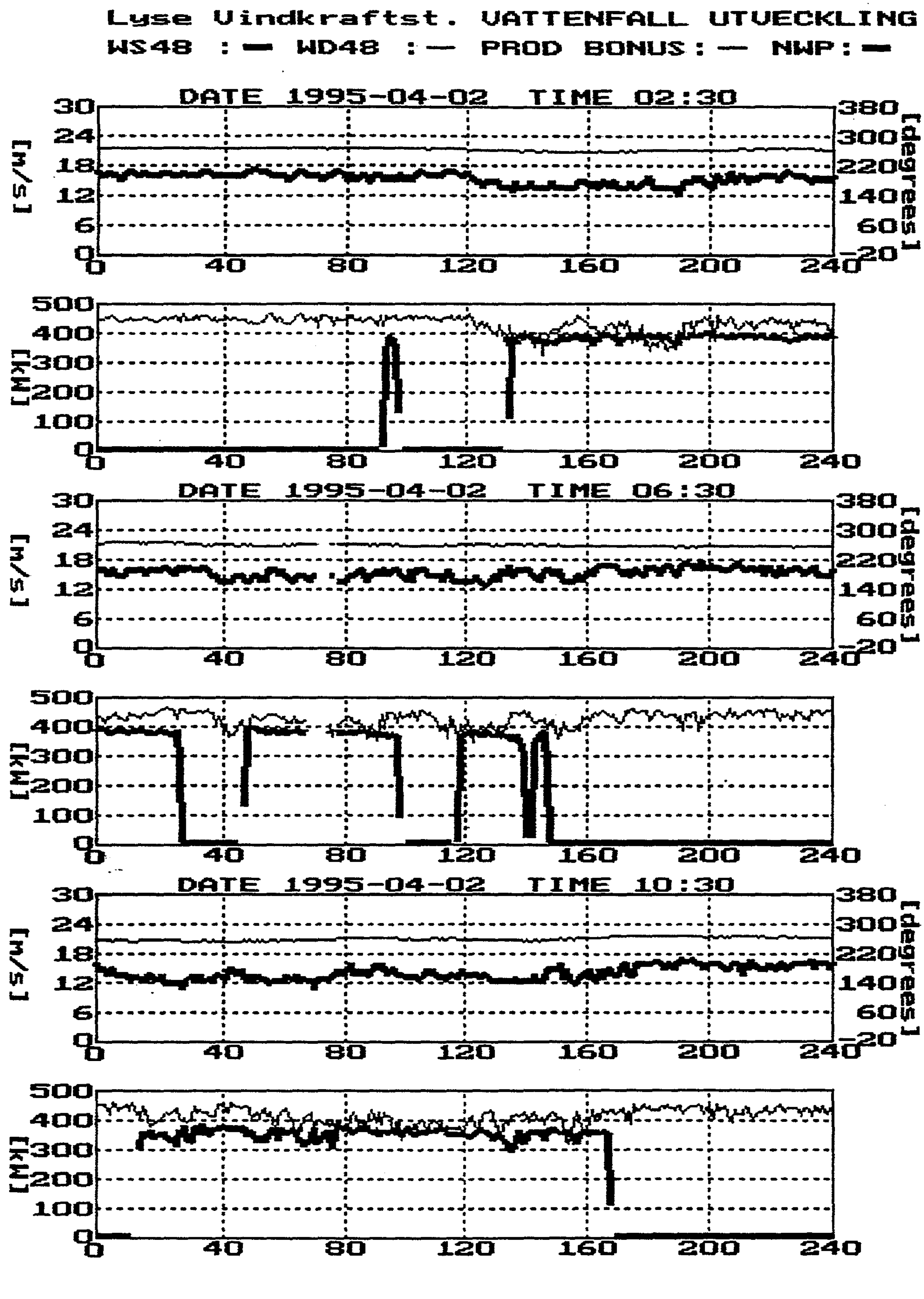


Figure 1.5:2 High wind speed case, 2 April 1995

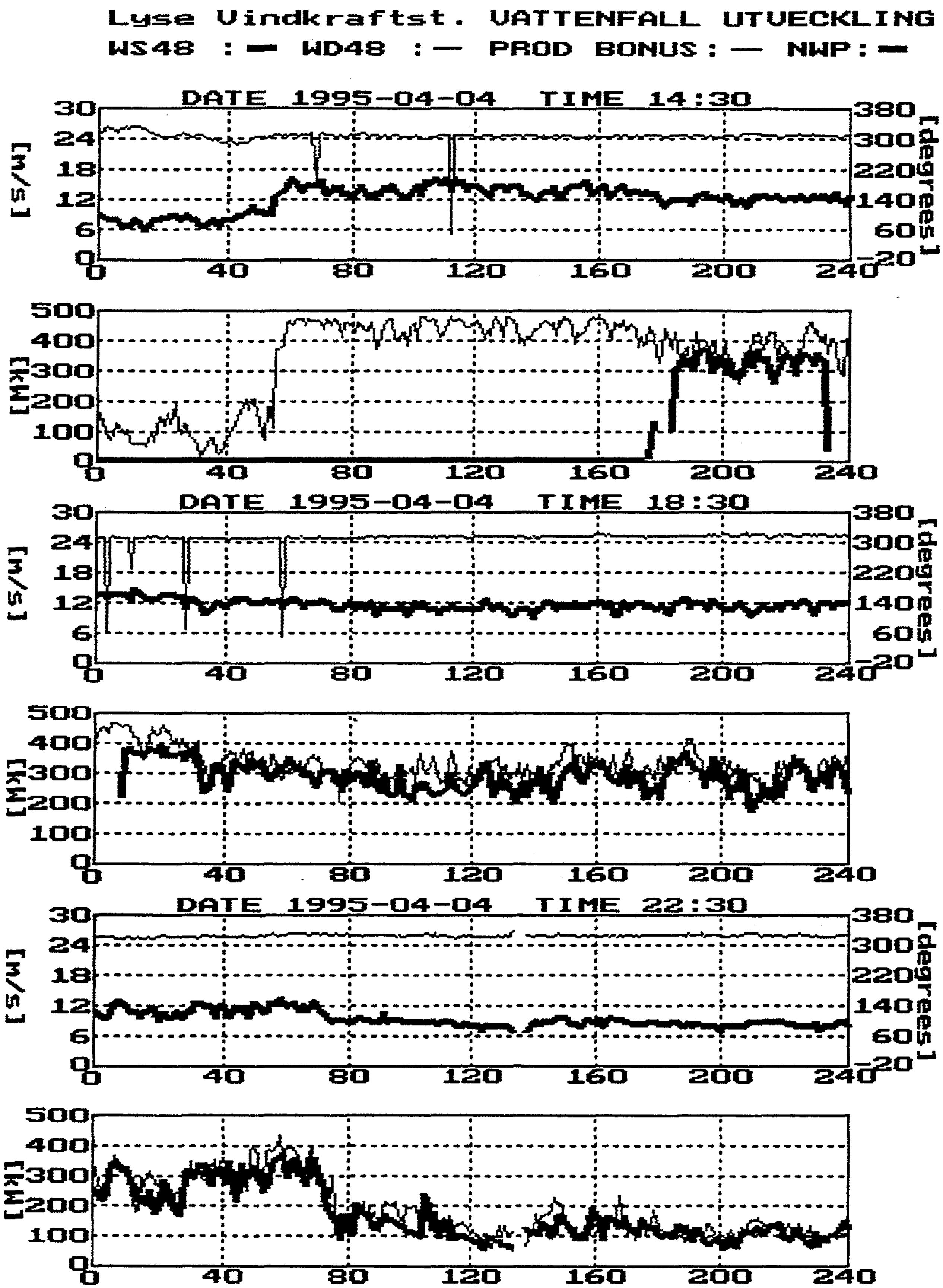


Figure 1.5:3 Fluctuating wind speed case, 4 April 1995

Real Time Graphs

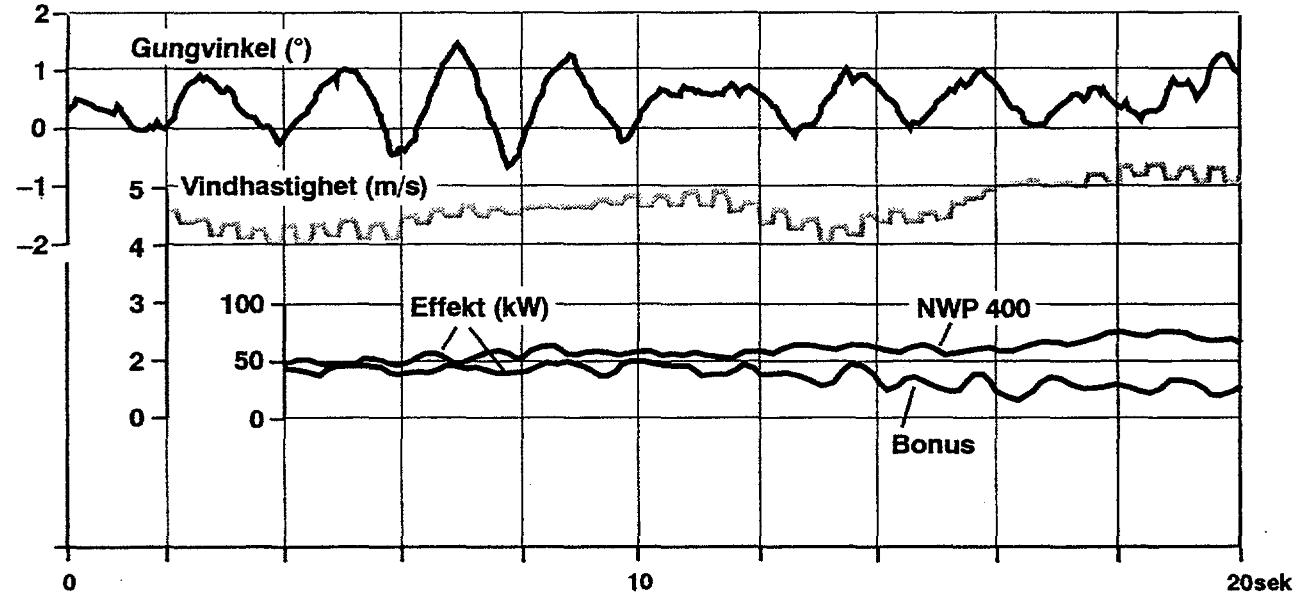


Figure 1.5:4 Low wind case. Note that plot includes teeter angle of NWP 400. Date 25 March 1994

2. PRODUCTION RESULTS AND OPERATING EXPERIENCES

2.1 PRODUCTION

This section covers the production statistics for the two wind turbines during the period June 1994 to May 1995 (12 month). All figures below are related to that period if nothing else is stated.

When reading the comparisons below and drawing your own conclusions it is essential to bear in mind that the machines are at different stages of development. Bonus 450 MkII is a serial production unit whereas NWP 400 is a prototype

The NWP 400 has undergone changes during the evaluation period which affects the statistics. Due to large teeter angles the control system had to be modified. The machine was stopped when the teeter angles exceeded a certain limit, which in practice means that the machine was stopped for wind speeds larger than approximately 14 m/s. This obviously resulted in a decreased energy production compared to what could have been expected.

The Bonus 450 MkII was also modified during the period. The control system was modified in order to have it operate satisfactorily in the type of terrain that exists at Basteviksholmen. Tests with stall strips were also done during the evaluation period in order to reduce power peaks.

The total production of the machines from the first grid connection (Bonus 17:th of June 1992 and NWP 15:th of September 1992) to May 1995 was:

NWP 400	1 024 MWh
Bonus 450 Mk II	2 848 MWh

Note! All energy production values were measured before transforming them to the utilitie's - Lysekil Energy's - 10kV-grid.

During the 12 month test period the two machines consumed 11.8 MWh and 447.5 MVArh.

Production figures were manually registered on the first day of every month.

2.1.1 Production and losses Bonus 450 MkII

Production to mains Bonus 450 MkII:	1092.3 MWh
Average production turbine on mains:	177 kW
Average production turbine calendar time:	125 kW

The losses in the Bonus 450 MkII are as follows;

Generator fan 2-step:	0.7/3.5 kW
Gearbox fan:	0.12 kW
Hydraulic pump:	0.37 kW
Yaw motor:	0.5 kW
Control computer:	0.1 kW

2.1.2 Production and losses NWP 400

The energy production from the NWP 400 was measured by a count unit connected to the control system.

Production to mains NWP 400:	696.5 MWh
Average production turbine to mains:	132 kW
Average production turbine calendar time:	80 kW

The NWP 400 was designed to operate with variable speed. This implied that a frequency converter (SAMI) had to be used. A frequency converter is known to have rather high power losses. An average of 94% of the generator production reached the mains from the frequency conversion system (SAMI). The 6% power loss included the control system, yaw motor, cooling fans, the computers for the evaluation program and the SAMI. The largest loss was in the SAMI. In all operation modes the SAMI had a base loss of 7.5 kW, this increased when the power increased. As an effect of this the small cabin, in which the SAMI was mounted, the temperature could rise up to a temperature of 44.3°C. In the wait mode the loss was supposed to be low, but was not measured.

The losses in the NWP are as follows;

Control cabinet:	0.5 kW
during yaw	2.0 kW
Fans (converter building):	1.3 kW
Gear oil cooling fan:	1.1 kW
SAMI converter, base loss :	7.5 kW
Measurement system:	0.3 kW

The SAMI converter losses has a base loss of 7.5 kW as mentioned above. This loss increases with increasing power production. The maximum loss at rated power, according to ABB, is 24kW. This results in an overall system efficiency of 90%, for generator and SAMI converter.

2.1.3 Possible annual production

Possible annual energy productions for the two wind power plants were calculated from the average wind data obtained from the MIUU measurement system in the meteorological mast at the site. The energy production calculations were based on the power performance curves delivered by the manufacturers, see also chapter 3.1 for a more detailed analysis.

The reasons for the deviations from the possible annual production are described in section 2.3.3. One reason for the large deviation for the energy production for the NWP 400 was the problem with too large teeter angles which led to a restriction in the operation of the machine. The wind turbine is stopped when the teeter angle exceeded a specific limit, this corresponded to wind speeds higher than approximately 14 m/s.

The Bonus 450 MkII had problems with too high power production. Tests with stallstrips were performed in order to lower the maximum power output. These tests took place in the period September 5 1994 to January 17 1995, which is within the evaluation period. The stallstrips reduced the maximum power output as supposed, but also reduced the power output at lower wind speeds which was not desirable. Parts of the stall strips were therefore removed. The differences between possible and actual production for the Bonus 450 Mk II is partly a consequence of the tests with these stall strips.

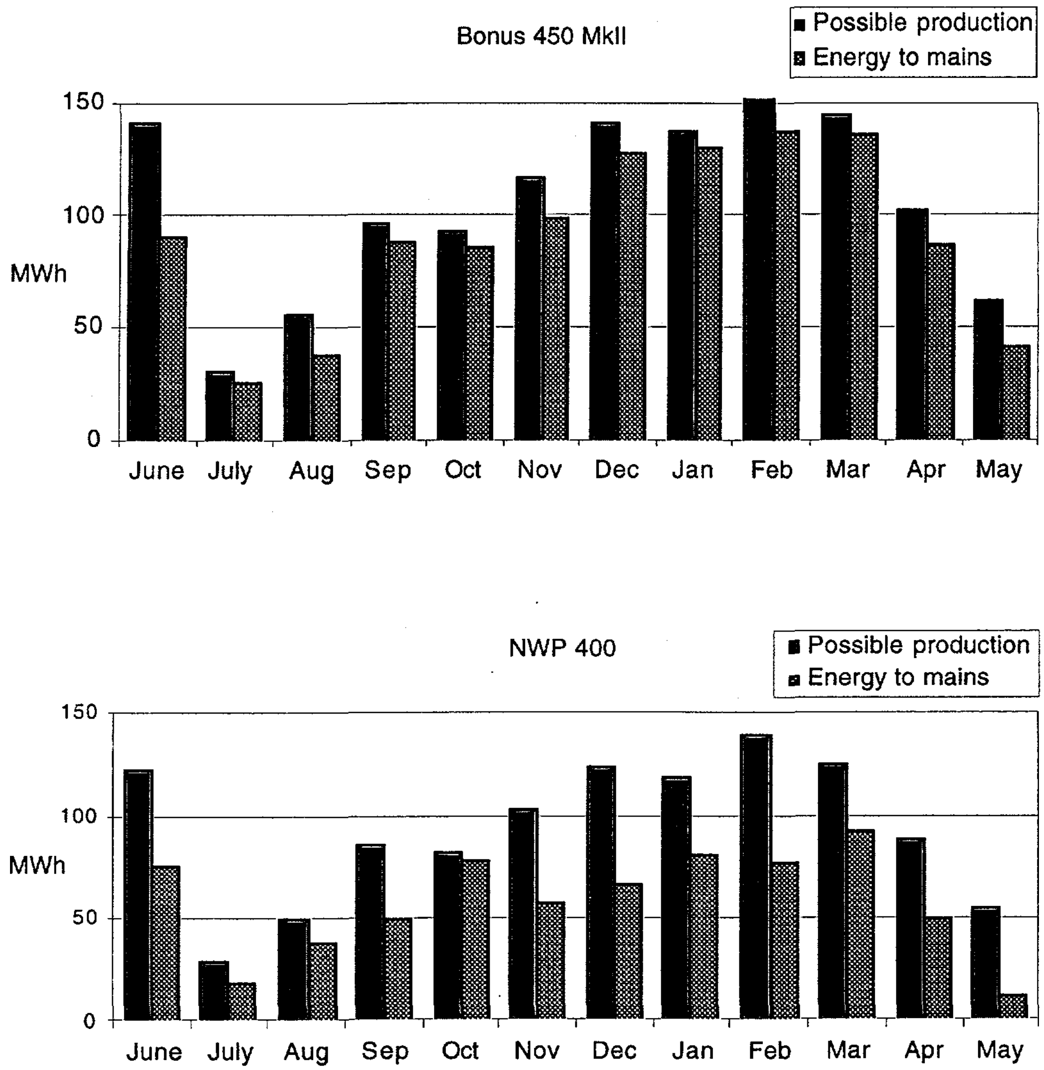


Figure 2.1:2 Possible and actually delivered energy to mains per month.

2.2 AVAILABILITY

2.2.1 Time availability

This is defined as:

(calendar hours of the month - hinder time) / calendar hours of the month.

The mean time availability for the12 months encountered was:
Bonus 450 MkII: 92.9%
NWP 400: 82.0%

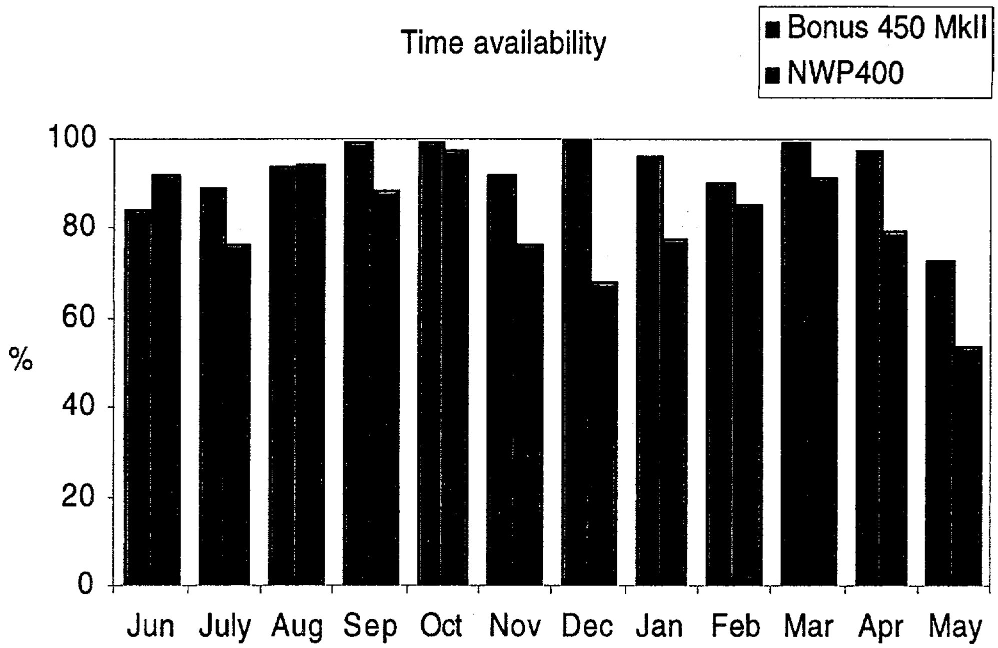


Figure 2.2:1 Time availability for both wind power plants

2.2.2 Production availability

This is defined as:

number of hours with generator on mains/ calendar hours of the month.

The mean production time for the 12 months encountered above was:
Bonus 450 MkII: 70,4%
NWP 400: 60,3%

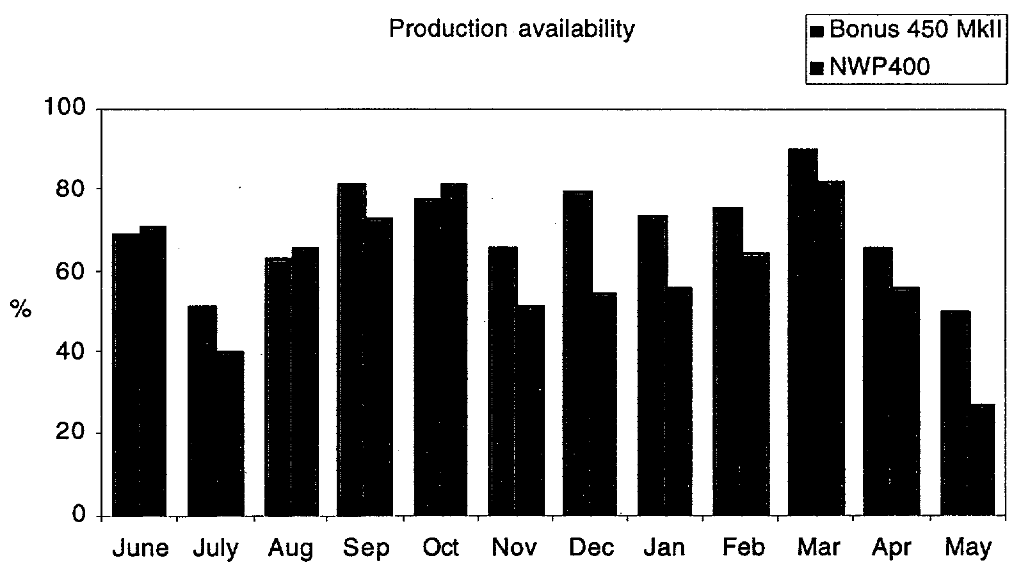


Figure 2.2:2 Production availability for both wind power plants

2.3 OPERATIONAL STATISTICS

2.3.1 Operational journals.

A written operational log was kept in the control room at Lyse wind power station where the operational and maintenance personnel could make notes. Log of alarms from the station was kept in the district control center.

Any fault on either of the two plants that would prevent its operation, closes a fault contact and triggers an "alarm-sender" connected to the telephone network, which sends a message to an alarm receiver located in the district control center, located in Trollhättan. The operator is notified that a problem has occurred. The operator contacts the machine that sent the alarm. Depending on the type of alarm that was sent the operator will acknowledge the alarm or send someone out to inspect the machine.

Operational information for the plants was presented separately for the two plants:

The control system of the NWP 400 saved all events and alarms on a hard disc in the control computer. Copies of this log was saved in the district control center in Trollhättan from where the machine was remotely controlled.

The Bonus 450 MkII has a built-in memory (eprom) which saves all events and alarms. This memory is cleared after a reboot of the control computer. Production statistics is saved in a memory, equipped with battery backup. The machine is remotely controlled from Trollhättan.

2.3.2 Operational modes of NWP 400.

In the NWP 400 control system the time in different types of operation were saved. The time of operation is classified using nine operational modes. The modes covered starts and stops, waiting for higher winds, different type of running, faults, tests and calibration. This type of information is not available for the Bonus 450 Mk II. Numbers of occurrences and duration of different operational modes is presented for the period of June-94 - May-95.

(8289 hours total with 10 seconds duration in the mode to be registered)

Operational modes:	Numbers:	Time(hours):	Numbers(%)	Time(%)
Low wind	1442	2042	3.6	24.6
Manual reg (manual)	209	475	0.5	5.7
Test (used by NWP)	1129	61	2.8	0.7
Acceleration (start)	1154	15	2.9	0.3
Retardation (stop)	1125	23	2.8	0.3
Optimal (running)	17843	3316	44.6	40.0
Stall (running)	16646	1584	41.7	19.1
Emergency (fault)	255	744	0.6	9.0
Inching (calibration)	163	29	0.4	0.3

Table 2.3:1 NWP operational modes

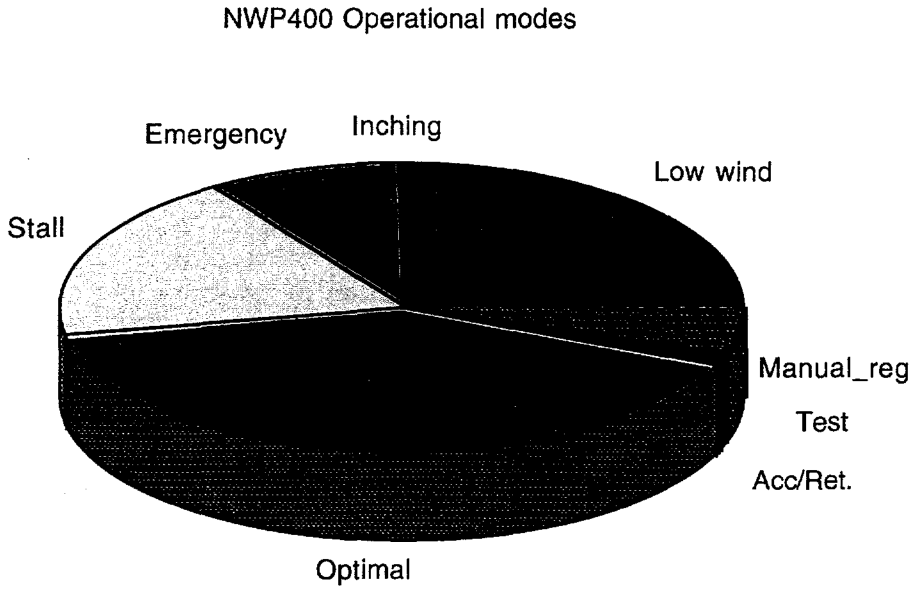


Figure 2.3:1 NWP 400 operational modes (time)

2.3.3 Statistics concerning hinder time for the power plants

2.3.3.1 NWP 400

The hinder time for the NWP 400 is shown in Table 2.3:2. The single largest item was the stops due to too large teeter angles. During the evaluation period the blade tips touched the steel tower near the maintenance hatch twice causing damage to the tips. The blade tips was repaired by the blade manufacturer. To avoid this problem the control system software was modified so it stopped the machine when the teeter angles became too large. After this restriction in the control system the machine has stopped frequently due to too large teeter angles. This mainly occurs in wind speeds exceeding 13-15 m/s. The machine is restarted when the wind speed has decreased to a level where a safe start can take place.

Other types of problems have also occurred which required modification of the control system. When the NWP 400 was started for the first time it was found that the frequency converter ABB SAMI produced a large number of high frequency disturbances to the main grid. It even made the Bonus 450 MkII stop due to "Frequency failure". During a period in autumn -92 the Bonus 450 MkII stopped every time the NWP 400 started. An extra filter was mounted to the SAMI to attenuate the disturbance, and this solved the problem. The frequency converter stopped two times due to internal faults. Trouble-shooting has taken quite a time and faulty thyristors and broken printed circuit boards have been replaced. These events occurred before the machine was taken over by Vattenfall. No signs of lightning could be traced but could be a possible reason. These events are not included in the statistics over hinder time, as they took place before the test period started.

In the beginning of may-95 the spline connection on the shaft between the generator and the gear box broke and caused a stop for about 2 weeks. After this repair the NWP 400 is now in full operation.

The machine was modified during its test operation and the problems that occurred have been eliminated. The machine behaves well on disruption/fault on the external grid.

Hinder:	Time (hours)
Teeter hub, vertical and horizontal angle	532
Broken spline connection	398
Control computer	143
Torque limit coupling	100
Corrosion	98
Brake faults, brake maintenance	98
Ice	84
Manual stops for evaluation program	77
Fault in frequency converter	28
Maintenance of measurment system	16
Service	46
External grid	12
Total:	1632

Table 2.3:2 Hinder time NWP 400

During the same time period the NWP 400 have been stopped 138 hours for "high wind". This was mainly due to low max. allowable wind settings in the control system in the beginning of the evaluation period.

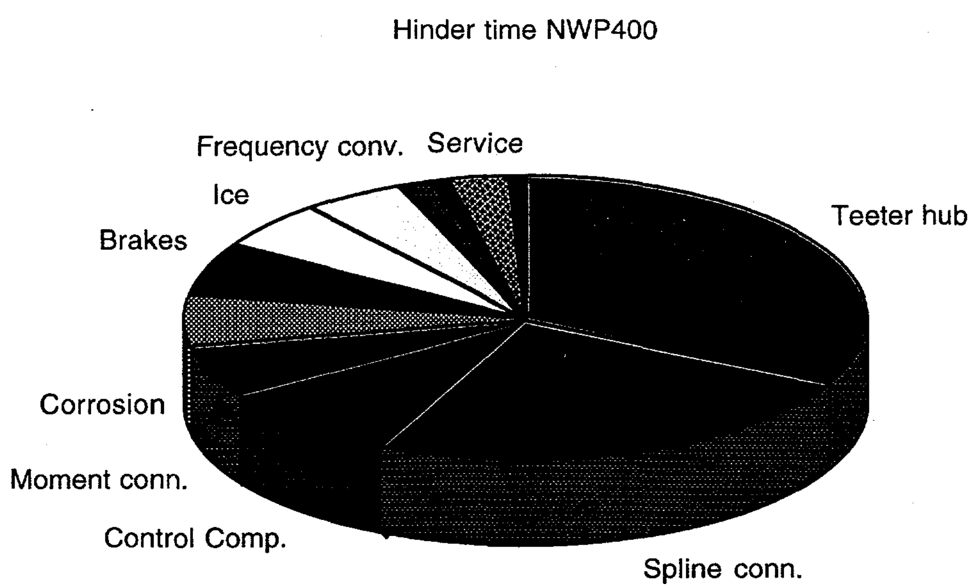


Figure 2.3:2 Hinder time NWP 400

2.3.3.2 Bonus 450 MkII

The Bonus 450 MkII:s hinder time for the past year probably reflected the problems that can occur on a conventional wind power plant.

The Bonus 450 MkII also had some problems with the control computer; both hard- and software problems have occurred during the three years of operation. Vattenfall choose the new Bonus WTC-2 control system consisting of a tower footing computer and a nacelle computer connected via fiber optics. The operating device/display could be connected to either of the computers.

In the first autumn/winter it became clear that the Bonus 450 MkII had difficulties connecting to the main grid. The reason was that the machine had been located in a rough and turbulent environment far from the Danish lowlands. The control software had to be re-coded as regards the connection to the mains and also at the same time debugged to get rid of some annoying events and alarms in the software that caused the machine to stop.

Another problem that occurred a couple of times was leakage from the pressure oil system. Once the swivel connection broke down and caused a main oil leakage. This is known to be a sensitive point as the manufacturer has chosen to distribute the pressure oil through the primary shaft to the hydraulic cylinders in the hub.

The machine behaves well on disruption/fault on the external grid.

Hinder	Time hours
Swivel connection	157
Brake problems (Generator cut-out due to brake error)	47
Thermal cut-off on generator	10
Anemometer failure	9
Overproduction on generator	112
Control computer	153
Yaw	62
Manual stops evaluation program	11
External grid	3
Service	56
Total	620

Table 2.3:3 Hinder time Bonus 450 MkII

During the same period Bonus 450 MkII stopped two hours for "high wind".

Hinder time Bonus 450 MkII

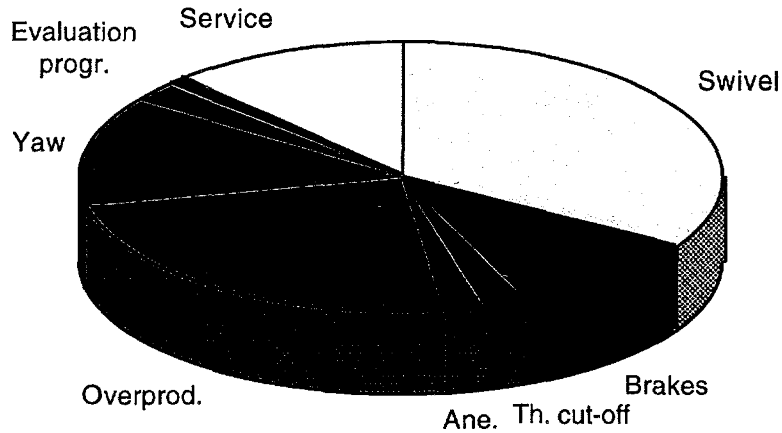


Figure 2.3:3 Hinder time Bonus 450 MkII june-94 - may-95.

2.4 MAINTENANCE

The operation and the maintenance were handled by Vattenfall's normal organization. The machines were supervised and remotely controlled from a control room that deals with both hydro power plants and the high voltage grid. Maintenance was carried out by the permanent staff which had trained in the systems that are special for wind power plants. Vattenfall Regionnät AB is in charge of the operation and maintenance of the machines. Historically it has always been the ambition of Vattenfall to maintain all of the equipment in operation and these two wind power plants are no exception. Vattenfall was fully maintaining the Bonus 450 MkII from the autumn -94 and the NWP 400 from spring -95.

Lyse Wind power station was the first and so far the only wind power plant operated and maintained by Vattenfall in western Sweden. Since the start in May-92 several alarms from the plant reached the district control center. In general, with our previous experience concerning hydro power, it is a fact that rotating machinery produces more alarms, than a normal supervised transformer station. However, with a well trained maintenance personnel we never had any problems with either of the station types.

The station is visited once a month when the personnel inspected both machines. Once a week the station is contacted by remote control from the district control center in order to check that it is operating properly. The plant in Lyse wind power station is operated and maintained like any other electricity production plant and can therefore not always get the highest priority when there is an alarm.

Alarms from NWP 400 were in majority, this is explained by the prototype nature of the machine. A number of maintenance and repair actions carried out on both machines are not included in this report since the machines were covered by guarantee from the manufacturers during that time.

2.4.1 NWP 400

On the 8:th of April 1994 the machine was delivered from NWP to Vattenfall, Business and Strategic Development. On the 1:st of May it was taken over by Vattenfall Västsverige, Dep. TR. From 1st of January 1995 both machines are owned by Vattenfall AB, Energy. The guarantee was expired on the 10:th of may 1995. Certain parts are to be fixed by NWP according to the guarantee inspection.

2.4.2 Bonus 450MkII

The guarantee (2 years) expired on the 22nd of October -94. At this time the manufacturer got some remaining items to fulfill together with extended guarantee on some replaced parts of the hydraulic system.

On the 2nd of August -94 stall strips were mounted on the blades, this was expected to reduce over-production. Later it became clear that this last action had a negative influence on the power production. Parts of the stall-strips were later removed.

2.5 OPERATION AND MAINTENANCE COSTS.

Maintenance personnel from Vattenfall presents a monthly time-report covering different activities performed at Lyse. The different activities are:

Inspection: The inspection time is estimated to 1 hour per month per machine involving 2 persons. This gives a total of 24 hours a year.

Maintenance Bonus: Parts of the costs for inspection is hidden in the maintenance cost, as the inspection sometimes can be performed at the same occasion as the maintenance takes place.
The travel time between Uddevalla and Lyse is also included in the maintenance time. It takes about 1 hour to travel to Lyse from Uddevalla and includes a ferry trip and 45 km in the car. The registered time during this year also includes participation in educational activities like changing of swivel, pitching blades and some guarantee items.

Fault alarm/Repair Bonus: When there is an alarm during working hours two persons normally go and during evenings, night and weekends one person. The shortest time needed for an alarm situation is then 2x4 hours or 4 hours. For security reasons there is a rule that there has to be two persons at the site for entering into the wind power plant.

Maintenance NWP: The figures include one 6-month service (performed by Vattenfall personnel alone for the first time). The previous 6-month service was performed by NWP-personnel (Guarantee).

Fault alarm/Repair NWP: The same personnel principles as for the Bonus machine. The work NWP personnel has performed on repairs is not included.

2.6 MATERIALS, CORROSION AND EROSION

The saline environment at the site is very aggressive and will reolutely attack any spot not protected by anti-corrosion agents. The problems with corrosion have been as follows:

Bonus 450 MkII : Corrosion on some caps for the pretensioned reinforcement has been observed. Pictures of the blades taken in july-95 presented in figure 1.3:2 show no signs of erosion.

NWP 400 : Corrosion on the bolts for the blade/hub-connection and on the caps for the pretensioned reinforcement on the base. This was dealt with in July-94 when the machine was treated with 2-component anti-corrosive painting and the caps were galvanized. Inspection later showed that the blade/hub-connection bolts were still rusty due to the fact that one can not easily reach the core of the problem on a site-mounted blade. Even some caps started to rust under the galvanization.

No sign of erosion was reported, see also figure 1.3:3.

2.7 LIGHTNING PROTECTION.

Faults due to thunder and lightning were reported as follows.

2.7.1 Bonus 450 MkII

The machine has since the erection during spring -92 been involved in the following disturbances due to lightning:

- Tripped main breakers TK51-S and G1-S by the shortcicuit-protection. However, this disturbance occurred before the manufacturer fixed the grid connection problem, as mentioned earlier in this document.
- Faults in the control computer occurred due to lightning.
- Broken lightning protection isolator coupled to the blade tip-wire. No damages on the blades were observed.
- The main grid had several faults due to lightning but this was not a problem to the machine. In fact, the Bonus 450 MkII can detect a small ground-fault on the grid due to the bias that appears in the fault-situation.

2.7.2 NWP 400

One fault in the frequency converter could be the result of lightning but this is not verified. The main grid had several faults due to lightning but this was not a problem for the machine.

2.8 ICE.

Faults due to ice was reported as follows.

2.8.1 Bonus 450 MkII

Problems due to ice was probably once a contributing factor to a fault on the machine. This happened on the 24th of November -93 at 00:15 am when the machine was to restarted after a power failure on the main grid. 23rd of November at 22:44 p.m. the machine stopped due to a power failure in bad weather i.e. high winds and heavy snow fall. The temperature was falling from +1 to -1 °C. Shortly after restart an alarm; "Generator cut-out due to brake error" was sent to the district center. The remote control program showed that the power output was 50kW in 10m/s wind. Inspection by personnel showed that one of the blade tips was out, braking the machine. The reason why the blade did not retract was that the wire had loosened from the lightning protection isolator which was broken earlier due to lightning.

2.8.2 NWP 400

10th of November -94 at 8:30 p.m. the machine stopped due to "high winds" shortly after stopping twice for "several horizontal teeter angles". When the machine restarted at 8 am the next day it soon stopped due to "GAP>>WS" (Generator Active Power greater than Wind Speed, i.e. more power than normally was required to start the power plant). Maintenance personnel was notified and discovered that the blades were covered with a thin layer of ice. This of course changed the aerodynamics of the blade and made the rotating mass unbalanced. The decision was taken to stop the machine until the ice thawed. The machine was started 14th of November at 11 am without any problems.

The meteorological phenomena from this period were described as follows:
On the morning of November 10 the temperature dropped below zero, at the same time relative humidity near ground was 92-93%. It is reasonable to assume that the humidity increases with height and it is not unreasonable to believe that the humidity at hub height was 100% and causing accretion.

2.9 COMMENTS ON OPERATION AND MAINTENANCE

SUGGESTIONS FOR CHANGES FOR FUTURE WIND TURBINE SYSTEMS

The personnel at Vattenfall, Trollhättan has operated the two machines for a couple of years. The following remarks concerning what can be changed for the future wind turbine systems are the opiniones among the staff at Trollhättan. The remarks are based on the ambition that the whole plant should be handled by Vattenfall permanent staff and there should be no need for specialists from outside Vattenfall to operate the wind power station.

- Both control systems seems old-fashioned and compared to other types of PC-based equipment these systems are complicated to use.

- Be aware of the need of special equipment that needs to be used for maintenance. These equipment and tools should be bought together with the machine.

- Specify acceptable levels of harmonics that can be accepted when buying machines where semiconductor technology is being used.

- The initial costs for wire-based communications have increased drastically. In the future the control systems should be designed for NMT/GSM communication.

- Manuals for operation and maintenance should be clear and easily understood.

- The frequency converter, ABB SAMI, is a type of equipment which will not easily be handled by the permanent staff at Vattenfall. Fault-localization and repair will probably not be possible to manage without help from expertise. This will of course also be costly.

- The type of brake lining that are being used in the NWP 400, needs post hardening before it can be used. This type of extra work should be minimized.

- It is easier to perform maintenance on the Bonus 450 MkII than on the NWP 400. The reason is that:
    - There are not as many components to maintain.
    - Access to the equipment is easier

3 TECHNICAL EVALUATION

3.1 POWER PERFORMANCE AND ANNUAL ENERGY PRODUCTION.

3.1.1 Summary

The evaluation was based on measured data from the time period October to December 1994. The relatively short time period was due to the requirement that both turbines should be in operation and no changes should be made to the turbines during the period. By this requirement the two turbines were exposed to the same wind conditions and a fair comparison of the two turbines could be made. Both turbines where equipped with "stall strips" during the studied period.

Here is presented the main power performance evaluation of the turbines within the project. A preliminary evaluation of the BONUS 450 turbine was performed earlier.

The annual mean power output for NWP 400, estimated from the measured power curve, is 117.6 ±9.7 kW assuming 100 % availability and a Rayleigh distributed annual wind speed of 7.5 m/s.

The annual mean power output for BONUS 450 is 132.0 ±10.8 kW. The uncertainty figures correspond to a 95% confidence interval.

Some figures and tables in this chapter are located at the end of this text in order to increase the readability.

3.1.2 Data Base

The evaluation was based on 10-min averaged data from the period 1:st of October to 31:st of December 1994. This data contain all necessary information required for the evaluation of power performance except for status and control signals and the number of accepted samples in each data set. Other sources of data were available in the project but these data were not as easily accessible and it was decided not to use them. The anemometer is located at 50.6 m above sea level in the meteorological tower on a boom pointing towards North-West. The hub heights above sea level for the NWP 400 and BONUS 450 Mk II turbines are 50 and 46 m respectively.

3.1.3 Selected wind direction sectors

Data, where the anemometer or turbine under test was in the wake of the meteorological tower or in the wake of other wind turbines, were discarded. The disturbed sectors are presented in the table below. The sectors to be excluded are taken from Figure 3.1:1. The values in the figure were suggested to be applied within the 'IEC standard procedure for measuring power performance'. The East sector was excluded due to the undulating and broken ground. The accepted sector was 198° to 319°.

Situation	Direction	Distance [m]	X/D	Excluded sector	Excluded direction
NWP wake->Met. Tow.	7.5	79	2.3	±48	319-56
BONUS wake->Met. Tow.	163	202	5.6	±32	131-195
BONUS wake->NWP	170	276	7.7	±28	142-198

Table 3.1:1 Excluded sectors due to disturbed turbine or disturbed meteorological tower.

3.1.4 Selection of data

In Figures 3.1:2-5 all uncorrected data are presented as scatter dots. Each dot corresponds to a 10-minute data set. As described above, information of the status and the control of the turbine was not included in the data base. A 'manipulation' of the data sets was therefore necessary. Data sets from abnormal operation were excluded by artificial means. All values falling far below the mean scatter swarm for the two turbines presented in the figures were excluded. The graphs show all data used in the analysis. No data was excluded from the data presented in the graphs. Almost no operational data existed for the NWP-400 turbine for wind speeds above 15.5 m/s during the studied period. The reason was that the turbine was not in operation in that wind regime.

3.1.5 Determination of Power Curves

The data were corrected for density variations and analyzed by using the Method of Bin. A 0.5 m/s wind speed bin width was used all over.

Figure 3.1:6 and 3.1:7 presents the power curves for the two turbines. The curves include standard deviation. The size (area) of the symbols are proportional to the number of values in each bin. The dotted curves represent the power curves according to the contracts between Vattenfall and the two manufacturers.

3.1.6 Uncertainty analysis on power curves

The evaluation of the uncertainty in the power performance testing presented in the following follows the procedure described in IEA Power Performance Testing, 2:nd edition. The basic physical relationship sought is the power output as function of wind speed. The test basically includes three measured quantities, power, wind speed and air density.

The sources of error include systematic errors such as calibration errors or site effect errors and random errors, errors related to scatter of the measured data points. The table below gives the bias errors used in the analysis. The turbines are located on a small island with several small islands at distances between 500 and 1500 m from the site. Some of the islands are relatively high (30-40 m). To account for the influence of the relatively complex surrounding and other unknown (but suspected) mast effects on the wind speed measurement the bias error was set to 4 %.

Instrument	Parameter	Estimated bias error for	
		NWP 400	BONUS 450
Anemometer	B(bin,v1)	0.5 % of actual	0.5 % of actual
Site effects	B(bin,v2)	4 % of actual	4 % of actual
Air density	B(bin,dens)	1 % of 1.225	1 % of 1.225
Power sensor	B(bin,p)	1 % of actual	0.5 % of rated

Table 3.1:2 Bias errors of the power curve measurement.

The resulting total error(Ur) was calculated by root-sum-squaring of the two error types, bias (Br) and random (Sr) errors:

$$U_r = \sqrt{B_r^2 + \left(t \cdot S_r\right)^2} \qquad (3.1:1)$$

where the constant t is chosen to 2. The probability of the true value to be within the interval Pow±Ur will therefore be approx. 95%.

The measured power performance curves and power coefficient curves plotted with the 95% confidence interval are presented in Figure 3.1:8 to 3.1:11.

The power performance of the two turbines is compared in Figure 3.1:12 and 3.1:13.

3.1.7 Annual mean power output and annual power production

The annual mean power output was calculated from the power curves by binwise summation of the production in each bin. A Rayleigh distributed wind speed is assumed. The binwise summation and weighing with the wind speed distribution gave the impact of power curve uncertainty on annual mean power output and annual power production. The table below gives the estimated figures for an annual mean wind speed of 7.5 m/s.

	NWP	BONUS
Measured Wind Speed interval (m/s)	4.25-15.75	4.25-20.25
Annual Mean Power (kW)	117.6 ±9.7	132.0 ±10.8
Annual Energy Production (MWh)	1030 ±85	1157 ±95
Annual Energy Production according to contract (MWh)	1096	1227
for Wind Speed Interval	4.25-23.00	4.25-20.25
Annual Energy Production according to contract (MWh)	1003	
for Wind Speed Interval	4.25-15.75	

Table 3.1:5 Annual energy production based on measured power curves and power curves according to contract.

3.1.8 Power quality for the NWP400 and BONUS 450 turbines

The evaluation of power quality follows the recommendations given in IEA Quality of Power single grid-connected WECS. The quality of power was evaluated according to the recommendation by determination of the normalized (with rated power) standard deviation of power, delivered to the grid, as function of wind speed. The treatment of the data was similar to the treatment of data for the power performance evaluation above. The variance of power during each 10-minute period was accumulated in bins. The standard deviation of power from each bin was normalized by the rated power. The values was for NWP-400 normalized by 400 kW and for BONUS-450 by 450 kW. The result is presented in Figure 3.1:14.

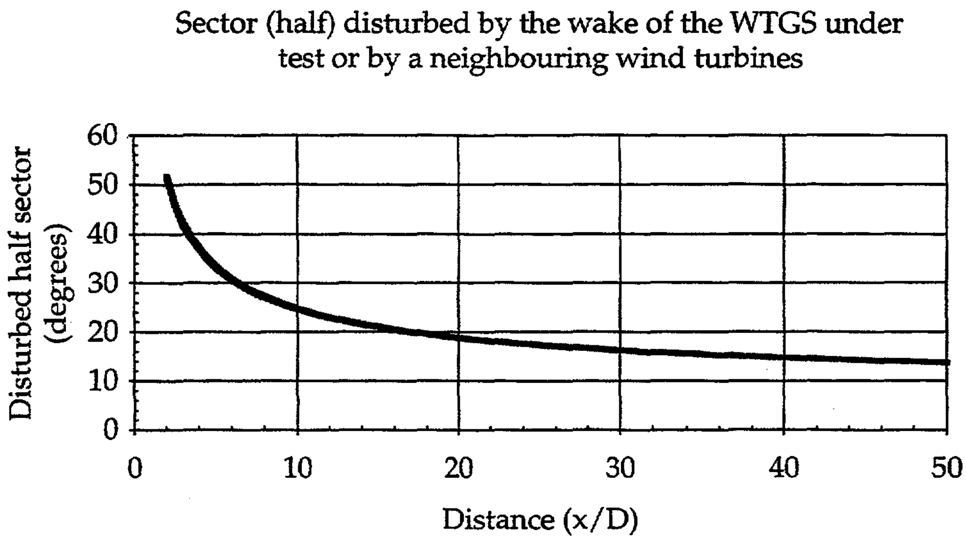


Figure 3.1:1 Wind direction sectors to be excluded due to disturbed turbine or disturbed meteorological tower. The values in the figure has been suggested to be applied within the 'IEC standard procedure for measuring power performance

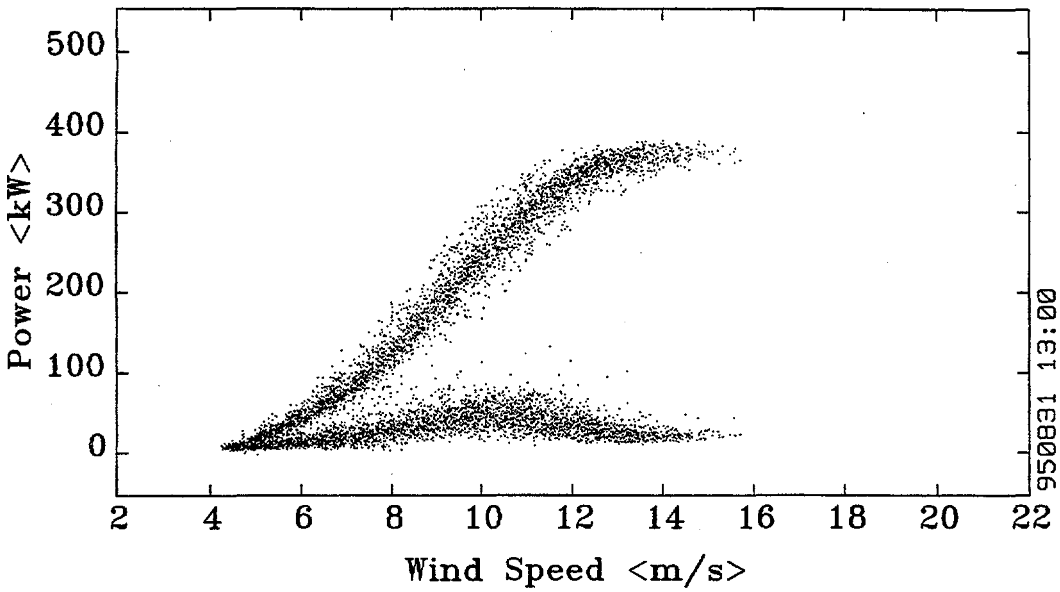


Figure 3.1:2 Scatter plot of mean and standard deviation from each 10-minute value vs wind speed for the NWP 400 turbine.

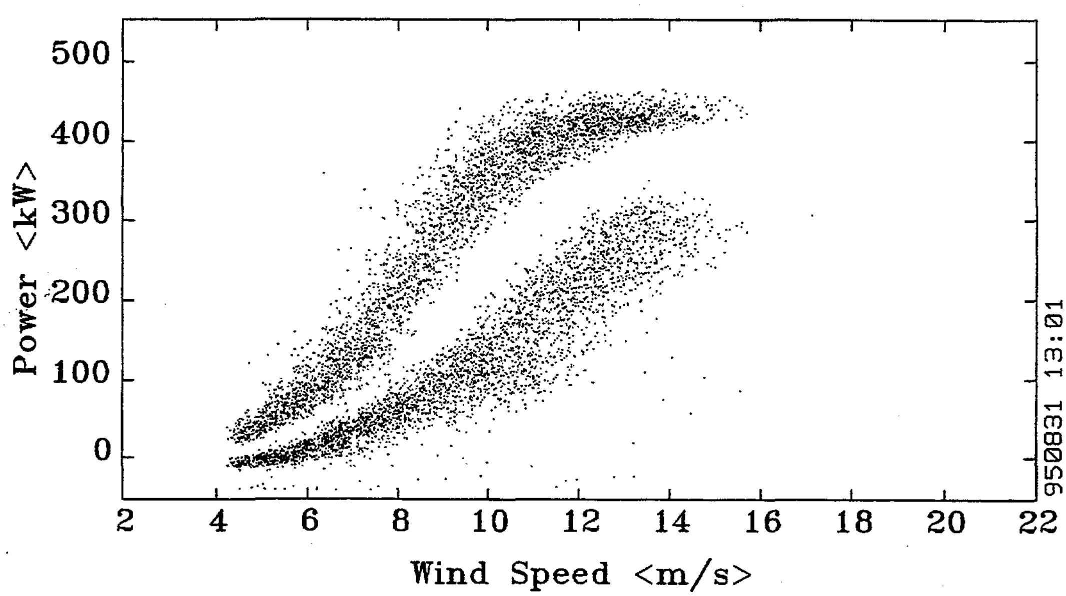


Figure 3.1:3 Scatter plot of maximum and minimum from each 10-minute value vs wind speed for the NWP 400 turbine.

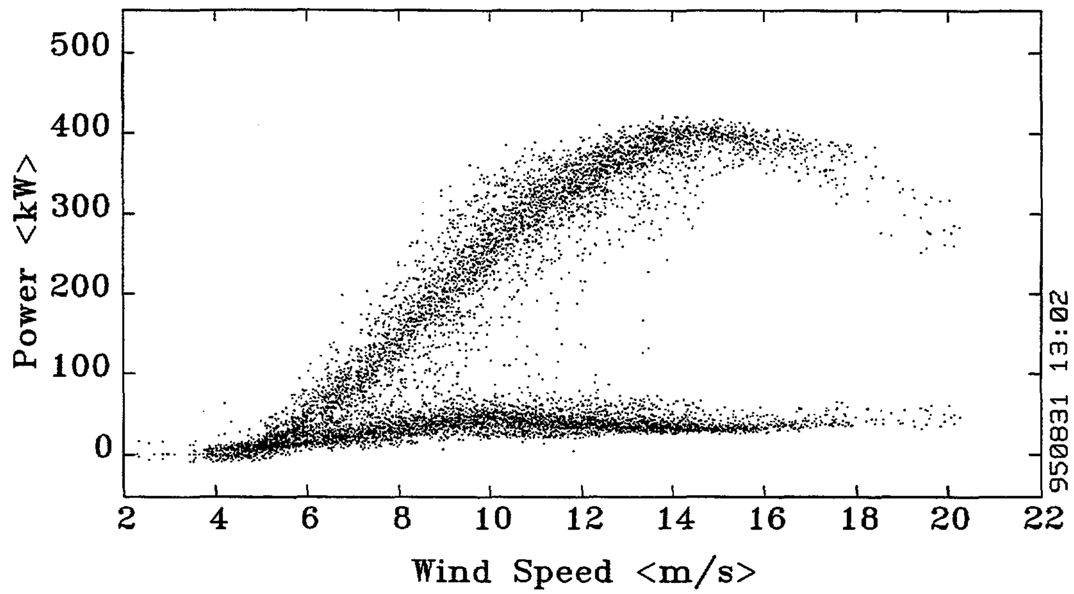


Figure 3.1:4 Scatter plot of mean and standard deviation from each 10-minute value vs wind speed for the BONUS 450 turbine.

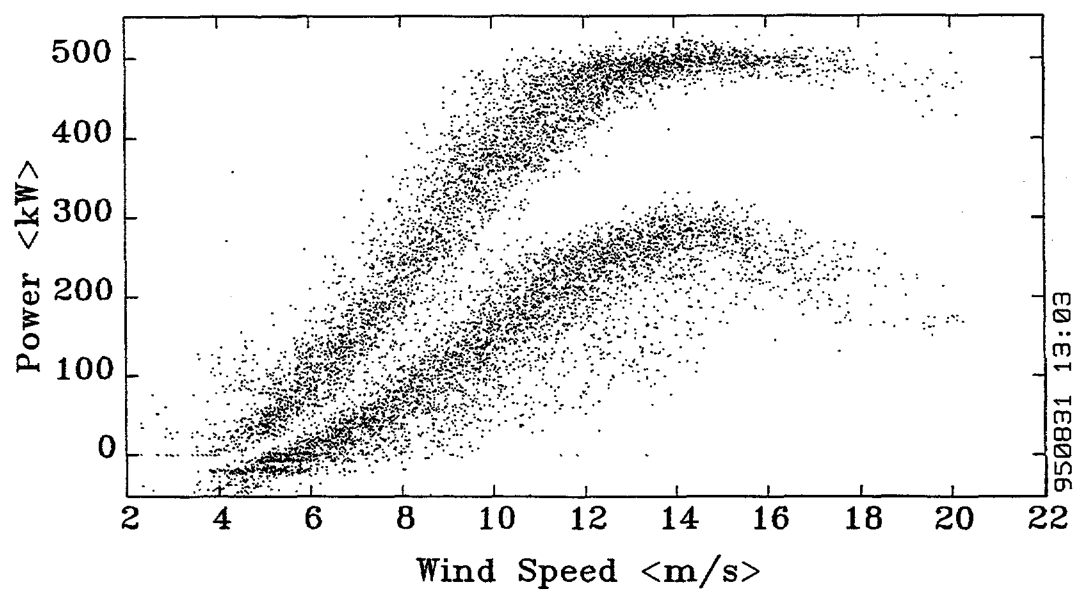


Figure 3.1:5 Scatter plot of maximum and minimum from each 10-minute value vs wind speed for the BONUS 450 turbine.

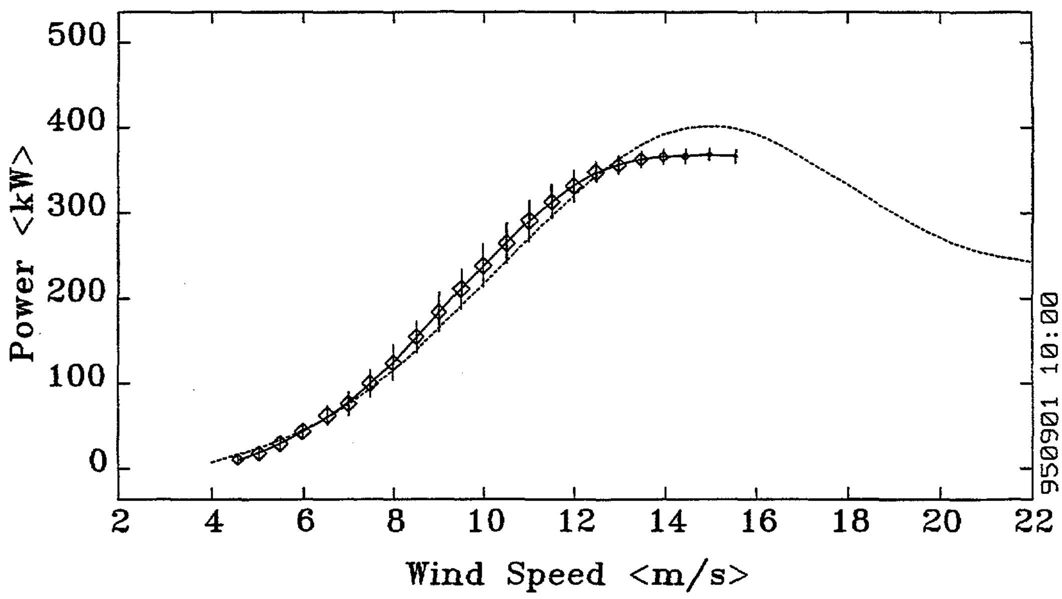


Figure 3.1:6 Power curve for the NWP 400 turbine including standard deviation and symbols proportional in size to the number of values in each bin. The dotted curve represents the power curves according to the contract between Vattenfall and Nordic Wind Power.

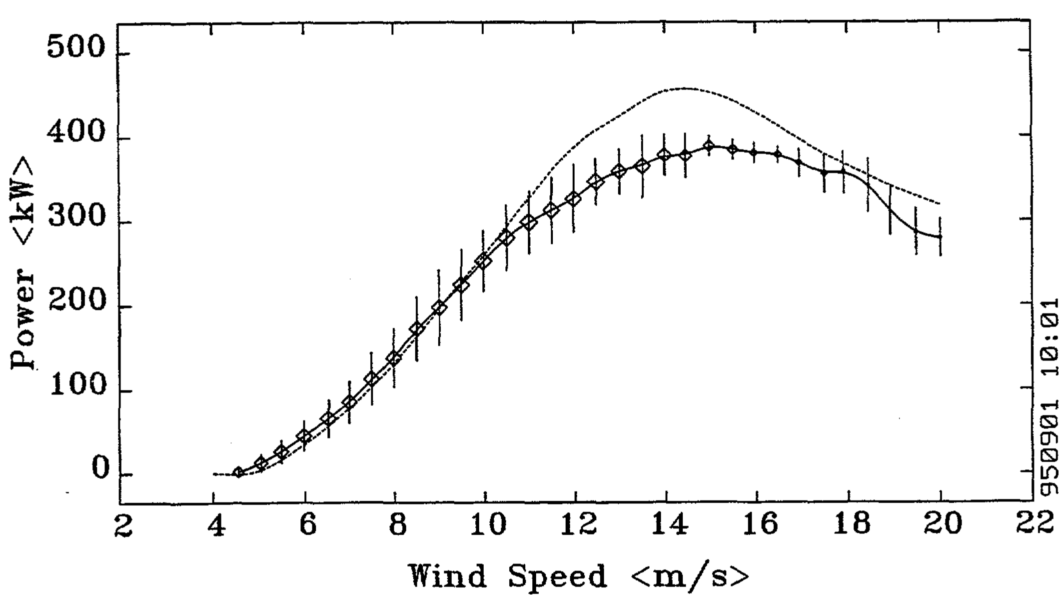


Figure 3.1:7 Power curve for the BONUS 450 turbine. The dotted curve represents the power curve according to the contract between Vattenfall and the Bonus Company.

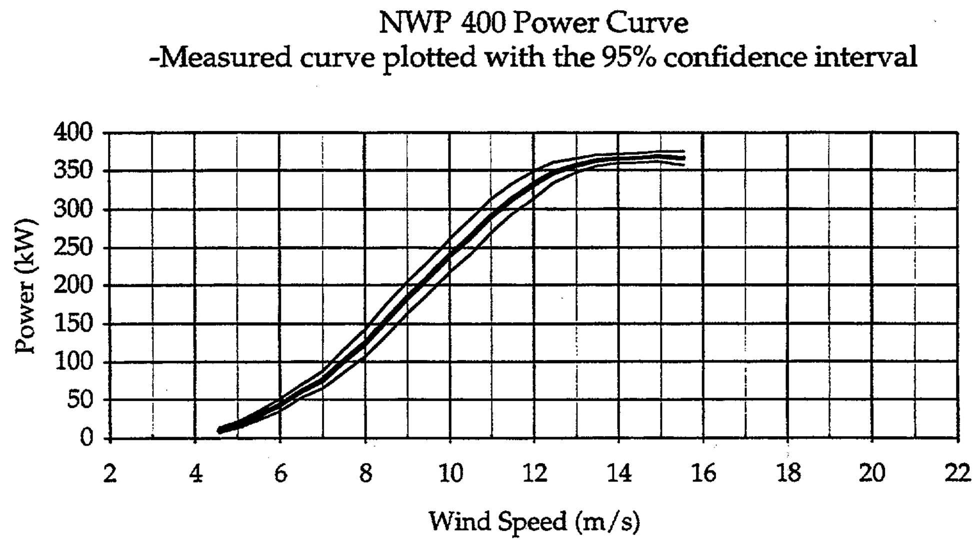


Figure 3.1:8 Measured power curve for the NWP 400 turbine plotted with the 95% confidence interval.

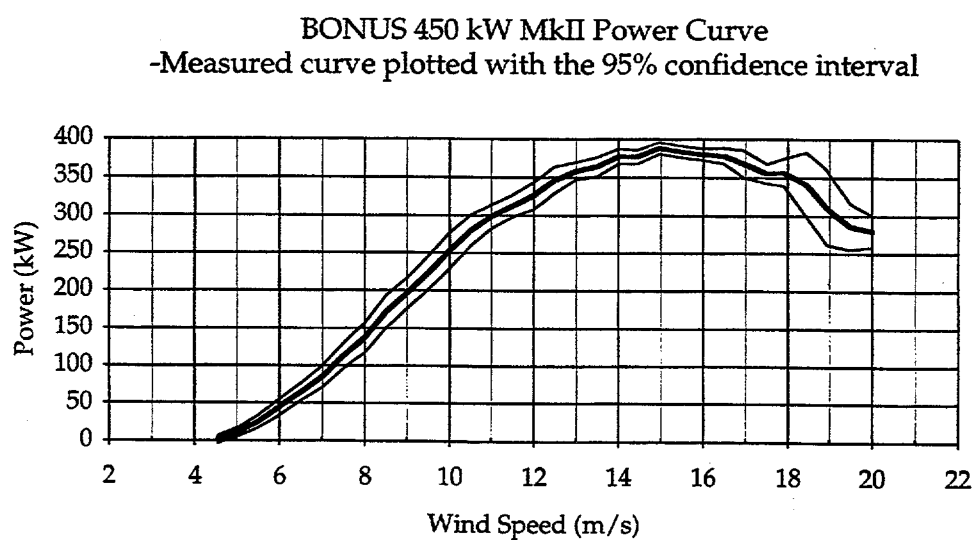


Figure 3.1:9 Measured power curve for the BONUS 450 turbine plotted with the 95% confidence interval.

NWP 400 Power Coefficient Curve
-Measured curve plotted with the 95% confidence interval

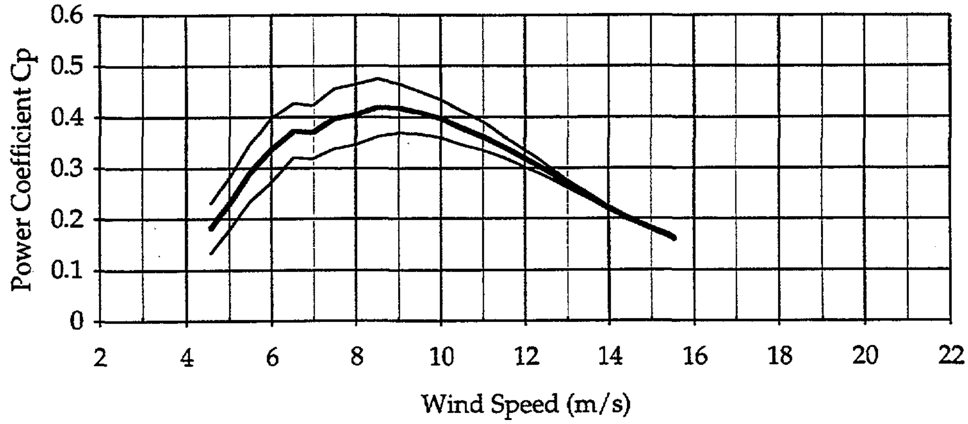


Figure 3.1:10 Measured power coefficient curve for the NWP 400 turbine plotted with the 95% confidence interval.

BONUS 450 kW MkII Power Coefficient Curve
-Measured curve plotted with the 95% confidence interval

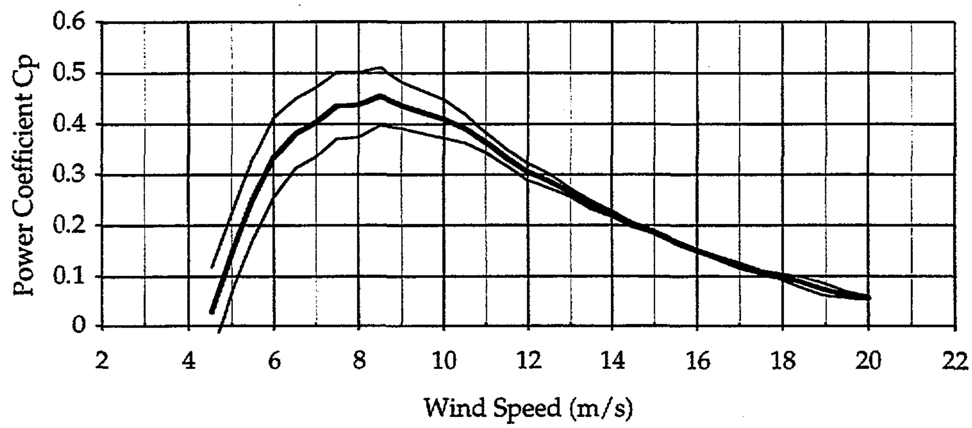


Figure 3.1:11 Measured power coefficient curve for the BONUS 450 turbine plotted with the 95% confidence interval.

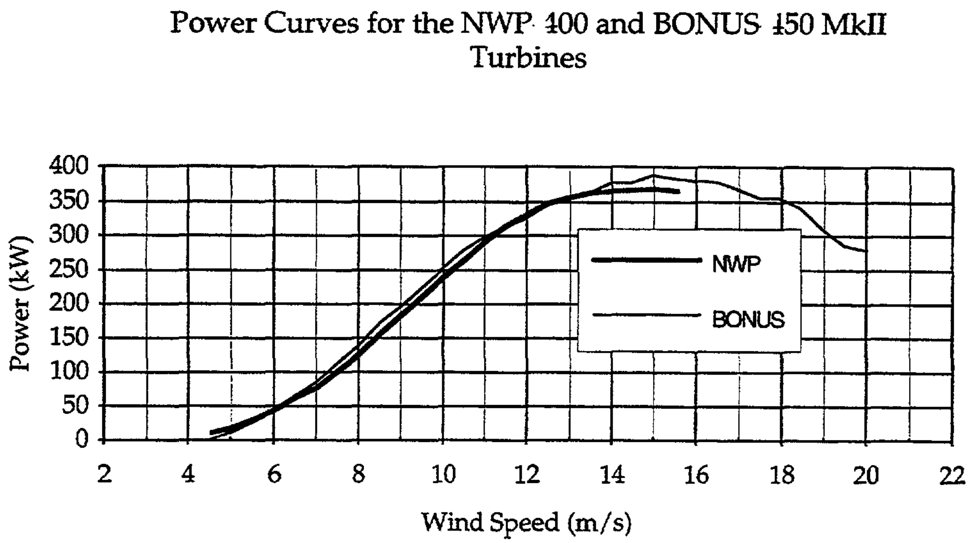


Figure 3.1:12 Comparison of measured power curves.

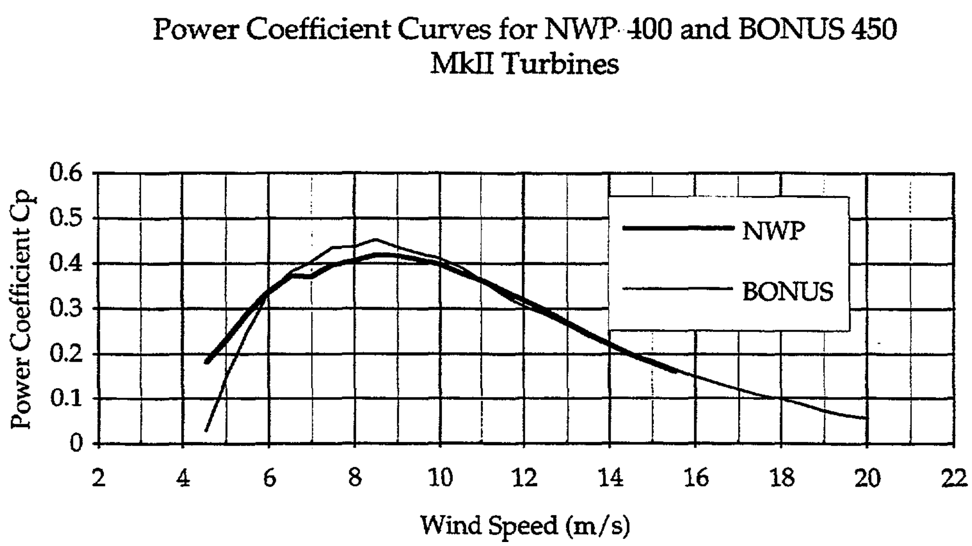


Figure 3.1:13 Comparison of measured power coefficient curves.

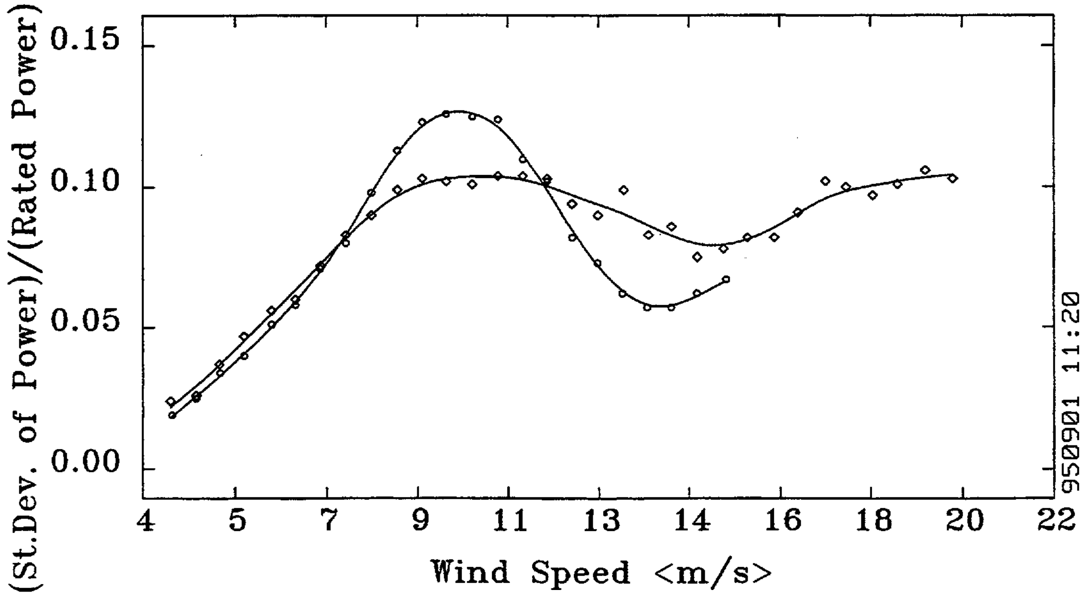


Figure 3.1:14 Normalized standard deviation of power for the NWP 400 turbine (circles) and the BONUS 450 turbine (diamonds).

3.2 AERODYNAMICS

3.2.1 Calibration of wind and power sensors

The objectives of these activities have been twofold. First the sensors have to be calibrated against the "true" values. The second objective was to enable the use of the control system registrations for evaluation purposes.

3.2.1.1 Wind speed

Although the wind around the nacelle is severely disturbed, it was possible to establish reliable relationships between the wind speed measured in the meteorological mast at hub height and ditto measured by the wind speed sensor on the nacelle (WSN). Due to different ways of data handling, the control and the measurement systems register different levels, although the same sensor is used. The calibrations are expressed as polynomials and implies that 15 m/s indicated may be interpreted as 12,9 m/s when registered by the measurement system and as 11,5 m/s when the control system is used. At 5 m/s indicated correct values are 5,3 and 4,3 m/s. The corrections are valid both when the turbine is operating and at standstill.

3.2.1.2 Wind direction

After each blade passage the wind direction sensor on the nacelle (WDN) is distorted 15 to 80°. Nevertheless it should be possible to calibrate a mean value with the meteorological mast wind direction sensor. However, when analysing the result (correction = -16°), it becomes evident that the uncertainty is about as large as the correction.

3.2.1.3 Power

The control system receives its power signal from the SAMI power conversion unit whereas the measurement system has its own sensor on the grid side of the electrical system. The calibration is expressed as a polynomials and implies that 400 kW registered by the control system corresponds to 375 kW in the measurement system.

3.2.1.4 Conclusions

It has been possible to calibrate the nacelle wind speed sensor and the control system power signal which means a future possibility for faster and cheaper evaluations. The nacelle wind direction sensor, however, was not possible to calibrate accurately enough.

3.2.2 Aerodynamic testing and evaluation

3.2.2.1 Blade tracking

During 1994 frequency analysis of the power output revealed that there was a 1-p (one per turbine revolution) component in the spectrum that was about the double height of the 2-p component. A l-p component normally is explained by some irregularities in the turbine. Video filming revealed that the blade tips were tracking differently (0,3 m). Blade angle measurements disclosed that the settings were slightly different (-2,2 and -1,7°). With both blades at -0,8° video filming in light winds indicated that they were now following the same track. A renewed frequency analysis revealed that the 1-p component now was less than the 2-p. Comparisons with the measurement and control system showed that obviously both these systems were inadequately calibrated, since they indicated wobbling of the rotor (that each of the rotor blades followed a cone instead of both rotating in the same flat plane) when it was non-existent, according to the filming and frequency analysis.

3.2.2.2 Power as a function of tip speed ratio

The blades were originally designed for a tip speed ratio of 8, but experience often demonstrated that the optimal performance was achieved at a higher ratio. The evaluation of test results when running at TSR of 8 and 9, however, revealed that the turbine performed its best when at a tip speed ratio of 8.

3.2.2.3 Blade pitch settings

The blade pitch setting was changed from -1,7/-2,2^{o} to -0,8^{o} as mentioned above. Below 11 m/s the power curve did not change. The mean top power, however, increased around 40 kW. Sudden max. power exceedances released the safeset coupling and necessitated a temporary decrease of the top RPM.

Besides general evaluation purposes, the intention was that the decrease in blade setting would increase the aerodynamic damping and thus decrease teeter excursions. This part is reported under section 3.3.6.4.

3.2.2.4 Stall strips

In April 1994 stall strips (length 0,8 m) were installed on the NWP 400 blades in order to minimise sudden max. power exceedances. When combined with an RPM increase from 38,2 to 39,3 the performance was retained at all wind speeds while decreasing power excursions. After the blade pitch decrease mentioned above the old strips were removed and new strips were installed (3x1,0 m). The change resulted in a notable decrease in power at wind speeds exceeding 8 m/s. At rated power the decrease was about 50 kW. One reason for this effect may be that the strips were installed somewhat too high on the leading edge of the blades. In order to restore the performance an adjustment of the pitch angle and/or partial removal of stall strips is planned.

3.2.2.5 Flapping moment

The behaviour of the flapping moment in relation to the wind speed is essential for the damping properties of the turbine. It has been possible to evaluate the flapping moment for the first stall strips configuration, but, due to a lack of measurement data, it has not been possible to evaluate the second configuration.

3.2.2.6 Airfoil characteristics evaluated from load measurements

The airfoil characteristics (Cl/Cd) have been evaluated from load measurements.

3.2.2.7 Conclusions

It has been possible to evaluate different tip speed ratios, blade pitch settings and installations of various amounts of stall strips. The evaluation of tip speed ratios revealed that the turbine performed its best when at a tip speed ratio of 8, which was the design value. The stall strip tests revealed that stall strips are an efficient way of minimising power excursions, however, care must be taken to avoid excessive losses of mean power. The flapping moment behaviour has been investigated in one configuration. Video filming and frequency analysis were utilised for checking and adjusting the blade tracking. The airfoil characteristics have been evaluated from load measurements.

3.3 STRUCTURAL EVALUATION

During the evaluation project, changes and improvements have been introduced on the turbine. The dynamic and structural evaluation has been concentrated on the turbine as it appeared around April 1995. Due to the teeter behaviour, the wind turbine frequently stops at wind speeds exceeding 13-14 m/s. The evaluation includes registrations of operation at a mast wind speed of 16,5 m/s. During its earlier history the turbine has been operated in a 22 m/s wind.

The structural evaluation covers frequency response, static and fatigue loads and movements, as well as the yaw and teeter behaviour of the turbine. Some extra effort has been focused on the latter two phenomena since these components are characteristic for the turbine and new in combination with a stall-controlled wind turbine.

The measured eigenfrequencies of the blades and the tower coincide with the calculated ones. The recognised asymmetries and couplings during operation are of marginal importance. There are no other exited eigenfrequencies that may present problems.

The design of the wind turbine has predicted measured loads and movements during normal operation, with a certain conservatism. The wind conditions were not underestimated in the wind description used for the design. Regarding normal operation and the actual version of the wind turbine, the fatigue life calculations have been based on a relevant input. It is likely that the prototype wind turbine installed will fulfil the fatigue life requirements.

The dynamic properties of the yawing system regarding the degree of damping and elasticity are in accordance with the design values. The yawing routine does not seem to work fully as anticipated, which may be a part of the explanation of the problems with large teeter angles. Frequent yawing in some situations may be explained by a yawing speed that is too high for the filtering performed. Due to the difficulties to calibrate the wind direction sensors it has not been possible evaluate the precision in the steering function.

At wind speeds exceeding about 13 m/s, the teeter angle increases and the phase angle stabilises. The wind turbine is frequently shut down due to large teeter angles at high wind speeds. The turbine is automatically restarted, although operational time is lost this way. Studied shut-downs have in common that they have happened in connection with an increase in wind speed or wind gradient, but not in connection with yawing, although simulations indicate that yawing was justified. Results from the analysis indicate that there are several ways of reducing the teeter angles to such an extent that shut downs will become less frequent than today.

3.3.1 General

The structural evaluation covers frequency response, static and fatigue loads and movements as well as the teeter and yaw behaviour of the turbine. Some extra effort has been focused on the latter two phenomena, since these components are characteristic for the turbine and new in combination with the wind turbine concept. Due to experienced problems with operation at high wind speeds it is also of great value to understand, verify and be able to modify these properties of the turbine in order to improve the operation availability.

During the evaluation project, changes and improvements have been introduced on the turbine. The dynamic and structural evaluation has been concentrated on the turbine as it appeared around April 1995. Due to the teeter behaviour, the wind turbine frequently stops at wind speeds exceeding 13-14 m/s. The evaluation includes registrations of operation at a wind speed, related to the meteorological mast, of 16,5 m/s (nacelle wind speed 19,6 m/s). During its earlier history the turbine has been operated in a 22 m/s wind speed.

3.3.2 Measurements and handling of data

The structural evaluation measurements were performed mainly with the data acquisition system (DAS) described in section 1.4. In some cases also data from the control system were used.

In all, 68 video8 bands were received from the DAS, each containing the measurement registrations from mostly two weeks. In order to make the data accessible for evaluation in decompressed files in chronological order, a comprehensive (about 15 hours per band on a 486, 50 MHz computer) editing work has been necessary. After editing the measurement data is available in 4-hour files each containing about 40 Mb. At the beginning of each file there is a special field with the constants used for transforming the binary values (2 bytes integer) into physical quantities for each channel. This means that access is secured to the original measurements, which gives a possibility to change transformation constants when new knowledge is available (calibrations etc.). Also signal conditioning, with the elimination of sudden jumps in signal levels, is best to do on the original registrations.

After editing, overview plots were produced, each revealing 24 hours of consecutive 1-minute mean, max and min values from all channels. They appeared to be a handy tool for selecting sequences for a deeper examination. In all they constitute 3000 pages, covering all measurements after January 1, 1994.

For a detailed examination of the measurements, various evaluation programs have been produced.

3.3.3 Natural frequencies and frequency response

The evaluation of the frequencies of the different properties of the wind turbine, such as forces, movements and accelerations, has in this case two objectives. One is to determine the natural frequencies of the wind turbine in order to make a comparison with the calculated values and as a base for updating the dynamic properties for verifying calculations. The other is to estimate the response of these properties at different RPM's.

3.3.3.1 Natural frequencies

The measurement of the natural frequencies of the wind turbine was performed with the turbine at stand-still on a day with a strong and gusty wind. In such conditions the varying wind load excites small oscillations in the construction, which are amplified where they coincide with the natural frequencies. The results of the measurements and of the calculations are depicted in Table 3.3:1. The measurements are analysed by FFT (Fast Fourier Transform).

With no exception the measured and calculated values coincide remarkably well.

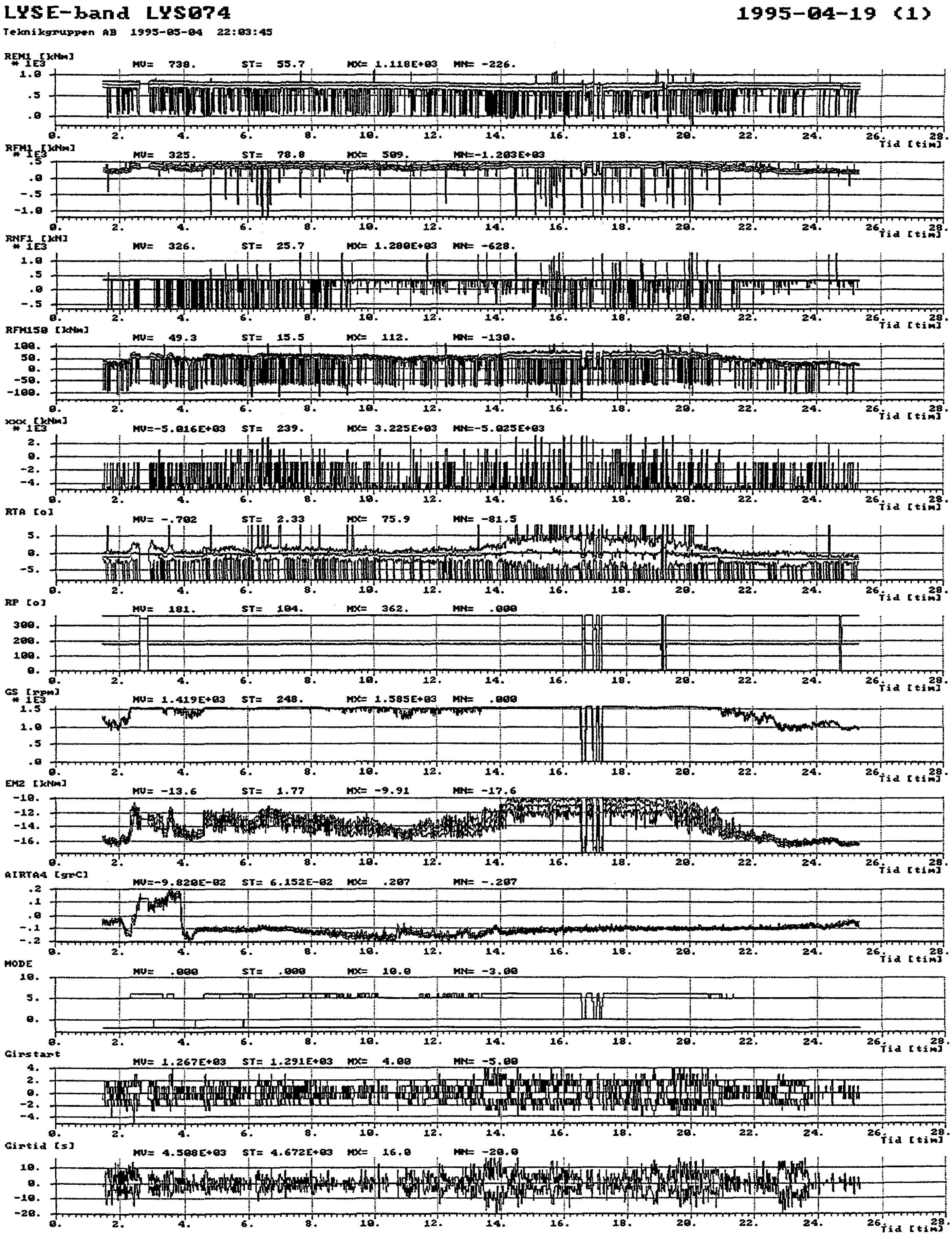


Figure 3.3:1 An example of an overview data plot (Page 1, April 19, 1995).

Property	**Frequencies [Hz]**					
	S-flap.1	Tower xy.1	C-flap.1	C-edge.1	Towerx .2	Tower y.2
Edge moment blade root 1 (REM1)		**0.45**	**1.5**	**3.13**	4.15	**4.87**
Flap moment blade root 1 (RFM1)	**0.3**	0.47	**1.5**	3.15		
Flap moment blade root 2 (RFM2)	**0.3**	0.47	**1.5**	3.15		
Flap moment 50% (RFM150)	**0.3**	0.45	1.58	3.2		
Tower moment roll (TMroll)		**0.45**	**1.5**			
Tower moment pitch (TMpitch)		**0.47**		3.2	**4.15**	
Tower moment torsion (TTOR)		**0.45**	1.7	3.2		4.8
Acceleration nacelle x (Xpp)		**0.45**		3.15	4.2	
Acceleration nacelle y (Ypp)		**0.45**				4.7
Acceleration nacelle z (Zpp)		**0.5**	1.55		4.2	
Rotational acc. nacelle x (Xpp)		**0.45**				**4.7**
Rotational acc. nacelle y (Ypp)		**0.45**		**3.2**	**4.3**	
Rotational acc. nacelle z (Zpp)	**0.3**					**4.7**
Acceleration tower 50% x (Tax)		**0.45**	1.5	**3.15**	**4.2**	
Acceleration tower 50% y (TAy)		**0.45**		3.15		**4.7**
Calculated	***0.3***	***0.47***	***1.6***	***3.1***	***4.15***	***4.8***

Table 3.3:1 Measured and calculated frequencies at stand-still. Those measured frequencies that are especially apparent are marked with **bold** letters.

3.3.3.2 Frequencies during operation

During operation, forces and movements will exhibit multiples of the rotational frequency, besides that it will also be possible to trace the natural frequencies. It is especially important to avoid that multiples of the rotational frequency coincide with natural frequencies that are poorly damped. How the even and odd multiples appear depend on

- the behaviour due to symmetrical and asymmetrical forces and due to the degree of coupling between different components,
- the way forces are transferred from the rotating to the fixed system,
- imperfections (asymmetries) in blades or in connections between the different components of the wind turbine.

The FFT-diagrams are presented in two versions, with the frequency expressed in Hz and p, i.e. in multiples of the rotational frequency. The advantage with the p-diagrams is that the degree of coupling to the rotational frequency is clearly demonstrated, see fig. 3.3:2

Also polar plots have been prepared, each revealing the signal level as a function of the turbine position during six consecutive revolutions. The oscillations often change their shape, which may be advantageous for keeping the stress level down, since it prevents that large amplitudes are developed. See fig. 3.3:3

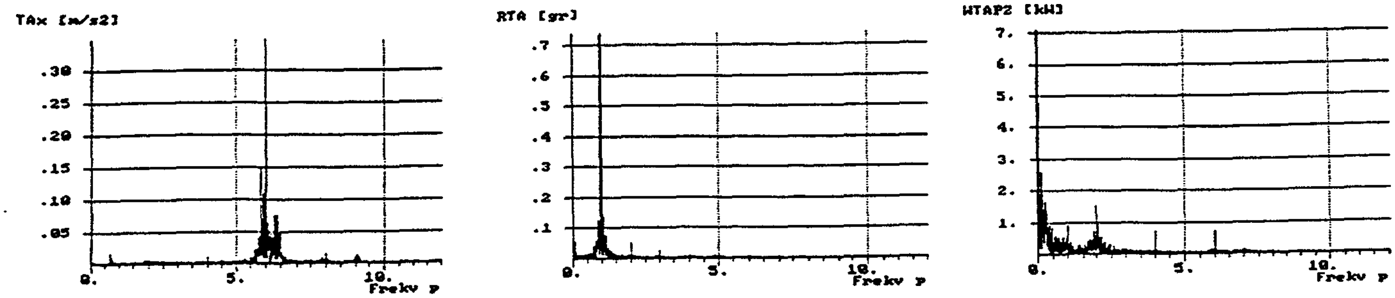


Fig. 3.3:2 Tower acceleration in the direction of the main shaft (TAx), teeter angle (RTA) and power (WTAP2), with the frequency expressed in p. Measurements from 1995-04-19.

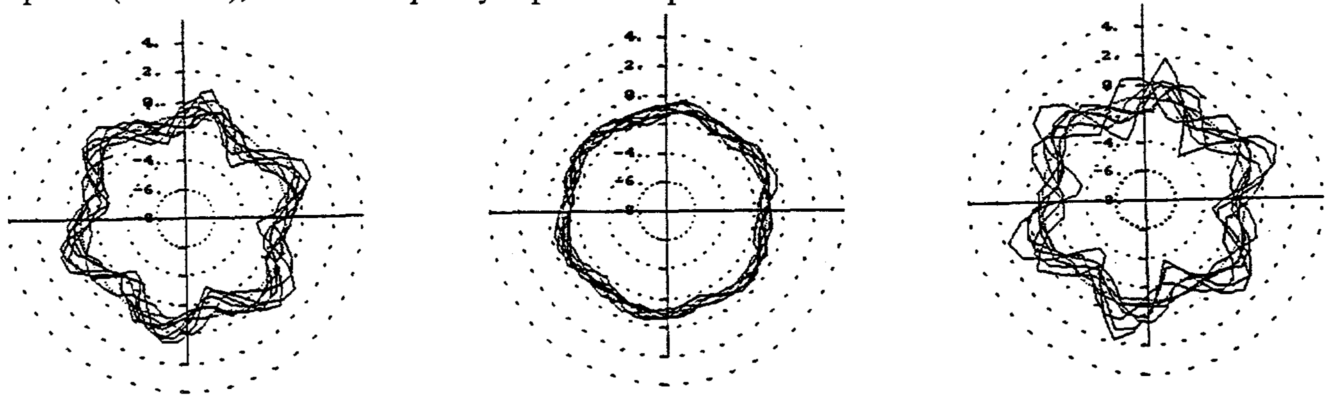


Fig. 3.3:3 Consecutive polar plots of the tower acceleration in the direction of the main shaft (TAx). Measurements from 1995-04-19.

Regarding the specific results, the following remarks are made:

- The tower accelerometer TAx demonstrates natural frequencies close to the even rpm 6p. These rather high acceleration levels, however, have little implication on the stress level, which is explained by the square dependency between acceleration and frequency.
- The coupling between C-edge and TM-pitch is weak. This means that the spring and damping properties of the yawing system are properly selected.
- Odd frequencies in the yawing system indicate the presence of asymmetries of the blades and/or in the yawing system. The 1-p component in the power spectrum is, however, now clearly smaller than the 2-p component. Note: since the measurements, here analysed, (April 1995) were made, additional adjustments have been made of the angles of the turbine blades. See section 3.2.
- The low rpm 0,43 Hz is close to the first bending mode of the tower 0,47 Hz, without any visible influence from 1p.
- At the low rpm there is a 0,15 Hz frequency of power and generator speed. This may be due to the way the turbine is controlled during optimal mode operation (variable rpm).

3.3.3.3 Conclusions

The measured natural frequencies of the blades and the tower coincide with the calculated ones. The recognised asymmetries and couplings during operation are of marginal importance. There are no other exited natural frequencies that may present problems.

3.3.4 Loads and load variations

In this section an overview of the loads and movements of the wind turbine during normal operation is presented. The objectives are twofold. One is to compare the measurements with the calculations in order to assess the degree of preciseness of the calculations. The other is to judge if the wind turbine is likely to achieve the stipulated fatigue life when exposed to the wind conditions of the site. The evaluation is based on measurements from the period January - April 1995. The characteristic components of this design, the teeter bearing and the yawing system, are discussed in sections 3.3.5-3.3.6.

3.3.4.1 Loads

The evaluation is based on measurements during three 24 hour periods during 1995 (January 7, February 3 and April 19). These days were selected because they covered the whole field of operational wind speeds.

The measurements are presented as dot diagrams, where the mean value, or the standard deviation, of the measured quantity during each turbine revolution is revealed as a function of the wind speed. In one example of such a dot diagram, Figure 3.3:4, the bending moment of the tower top is shown.

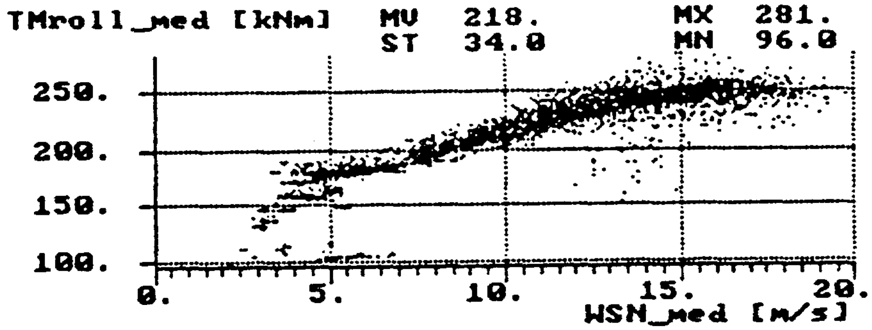


Figure 3.3:4 A dot diagram of the mean value of the bending moment in the tower top, TMroll, as a function of wind speed. From 1995-02-03.

The measurements that have been judged against calculations have been selected because comparisons are meaningful and reasonably accurate measurements are available. One general problem has been variations in the levels of the measurement values, probably due to influence of the temperature on the signal amplifiers.

Two types of calculations have been used. The Rain-Flow-Count-based (ref. H Ganander and H Johansson: Fatigue Design by Using a Modified RFC Description of the Wind. Windpower '88, September 18-22, 1988. Honolulu, Hawaii.) calculation from 1991 was used for the original fatigue assessment. It shows the wind turbine response at successively increasing wind speed and is well suited for comparisons with the measurement dot diagrams mentioned. An up-dated calculation was produced in 1993. There is also a recent simulation (1995-06-22) based an up-dated description of the wind turbine and the way it is controlled. The wind input is a simulated wind field with a duration of 500 seconds. This calculation is the one that is most accurate in details.

- The variation of the measured edge moment on blade 1 (REM1) is dominated by the influence of gravity. The level is unstable due to the mentioned problems with the measurement system.
- The measured flap moment on blade 1 (RFM1) reveals a width (max-min) of 180 and a standard deviation of 17 kNm, to be compared with 215 and 20 kNm respectively in the calculations.

- The measured acceleration along the nacelle (Xpp) has an offset in the signal level, but the increase of 0,15 m/s^2 in the mean value when the wind shifts from 5 to 15 m/s can be translated to a 0,88^o increase of the pitch angle of the main shaft, to be compared with the calculated value 0,99^o.
- In the same way the measured acceleration transverse of the nacelle (Ypp) can be translated into a roll angle of the tower top of 0,19^o, to be compared with the calculated value 0,18^o.
- With increasing wind speed, the yawing moment decreases, as is postulated by the calculations. The standard deviation, however, increases, which is also foreseen in the calculations.
- The absolute levels of the bending moment at the tower top (TMroll and TMpitch) are uncertain due to the temperature influence. However, the increase with wind speed is well in accordance with the recent Vidyn-simulation. These tendencies are not so evident in the RFC-calculations.

3.3.4.2 Wind conditions

The description of the wind conditions used when designing the NWP 400 were based on available measurements from Näsudden and Alsvik in matrix form. Modifications had to be introduced in order to compensate for the low sampling rate at Näsudden and for the complex terrain at Lyse. For the asymmetrical wind gradient, which is of prime importance for the fatigue life of a wind turbine, a value of 60 mrad/s was assumed for both the mean value and for the standard deviation. Calculations were performed for values of -180 - 300 mrad/s.

The wind measurements at Lyse, which are thoroughly described in section 3.7, revealed at a height of 49 m for the asymmetrical wind gradient a mean value of 50 and a standard deviation of 30 mrad/s, which means that the values mentioned above are conservative. Due to the way the comparison was made, it also indicated that the turbulence levels were not more severe than postulated.

3.3.4.3 Fatigue life

The information earlier related in this section reveals that the design of the wind turbine, with a certain conservatism, predicted measured loads and movements during normal operation. The wind description used during design does not underestimate the wind gradients and turbulence levels at the site. As far as normal operation and the actual version of the wind turbine is concerned, the fatigue life calculations have thus been based on a relevant input. These fatigue calculations were checked during the design phase by Det Norske Veritas and others.

In order to make a prediction of the fatigue life of the prototype wind turbine actually installed at Lyse, measurements that cover all the versions and modifications would have to be available. Since this is not the case, no formal statement can be made regarding the fatigue life of this prototype sample. However, since the modifications have been limited, it is likely that the statement above is valid also for the prototype turbine currently installed.

3.3.4.4 Conclusions

The design of the wind turbine has predicted measured loads and movements during normal operation, with a certain conservatism. The wind conditions were not underestimated in the wind description used for the design. Regarding normal operation and the actual version of the wind turbine, the fatigue life calculations have been based on a relevant input. It is likely that the prototype wind turbine installed will fulfil the fatigue life requirements.

3.3.5 Yawing system

The yawing system is of primary importance for the proper operation of the wind turbine. It has two functions. One is to steer the nacelle with regard to the wind direction. The other is to form a soft and damped connection between the nacelle and the tower.

Since the NWP 400 was taken into operation during the fall of 1992 certain modifications with an impact on the yawing behaviour have been introduced. After the blade tip incidents during 1993 the teeter spring stiffness was increased. The original yaw motor, which was a digitally controlled stepping motor, was replaced by a standard on-off controlled induction motor.

The measurement system yaw position indicator, YP, was replaced with a new one with better resolution on April 6, 1995. The analysis is based on measurements on this version of the wind turbine, from April 1995.

3.3.5.1 Dynamic properties

The dynamic properties of the yawing system regarding the degree of damping and elasticity have been evaluated. They have been found to be well in accordance with the anticipated values.

During operation the yawing moment decreases with increasing wind speed, although the variations increase.

3.3.5.2 Yawing function

The yawing routine that is utilised in the control system of the NWP 400 has been analyzed and tested in various ways. It is based on control of the yaw angle based on both the wind direction sensor and a measurement of the horizontal teeter angle. When simulating the routine, the results differed from those obtained in the control system. This may be due to differences in filtering and sampling or that the control system computer instantaneously has to much to do. The consequence may be that, although the yawing function most of the time is performed as anticipated, there may e.g. be situations when yawing is not performed when it should be. This can have implications on the problems with large teeter angles related in section 3.3.5. The matter is not yet fully investigated.

During some periods yawing is performed as often as once every five seconds, with little net yaw movement. This may be due to a yawing speed (2^{o}/s) that is too high for the filtering performed.

As pointed out in section 3.2.1, it was not been possible to calibrate the wind direction sensors accurately enough to evaluate the degree of preciseness in the steering function. The problems related above however have nothing to do with this lack of accuracy.

3.3.5.3 Conclusions

The dynamic properties of the yawing system regarding the degree of damping and elasticity are in accordance with the design values. The yawing algorithm does not seem to work fully as anticipated, which may be a part of the explanation of the problems with large teeter angles. Frequent yawing in some situations may be explained by a yawing speed that is too high for the filtering performed. Due to the difficulties to calibrate the wind direction sensors it has not been possible to evaluate the precision in the steering function.

3.3.6 Teeter dynamics

The NWP 400 wind turbine is equipped with a teeter hub, which constitutes a soft connection between the main shaft and the rotor. The maximum possible teeter angle is 7,5^{o}. After the blade tip incidents during 1993 it was revealed that, although both incidents had happened in connection with break downs of the yawing system, the blade stiffness in flap direction was around half the value that had been assumed during the design phase. This implicated that if maximum blade deflection and maximum teeter angle occur simultaneously and towards the tower, the blade tips will hit the tower, as had happened. Although the risque of a tip impact in principle is easy to eliminate on a new wind turbine, considerable efforts had to be devoted to this problem on the prototype turbine. The teeter spring was strengthened with a factor of four. A limit for the allowable vertical teeter angle was introduced in the control system. The yawing motor was replaced. Since then no more blade tip incidents have happened, although the turbine is frequently shut down due to large teeter angles at wind speeds exceeding 13 m/s. The turbine is automatically restarted, but considerable operational time is lost this way. During the evaluation much attention has been focused on the problem, as reported here and in section 3.2. The report is based on measurements conducted during 1995.

The evaluation of the teeter behaviour has been conducted towards two objectives. One was to investigate the amplitude and phase behaviour of the teeter angle in normal operation. The other was to study situations with large teeter excursions that have caused shut down of the turbine.

3.3.6.2 Teeter dynamics in normal operation

A statistical description of the teeter behaviour during normal operation has been obtained from point diagrams (see section 3.3.3.1), where the mean, max, min and standard deviation of the teeter angle (RTA) during single turbine revolutions were been studied as a function of the wind speed (WSN) and the relative wind direction (WDN).

It is observed that, at wind speeds exceeding about 13 m/s, the teeter angle increases and the phase angle stabilises at around 210^{o} (0^{o} is when a blade teetering towards the tower is pointing upwards).

3.3.6.3 Turbine shut-downs due to teeter exceedances

Measurements from turbine shut-downs due to teeter excursions were been studied in connection with additional information from simulations of the yaw behaviour, based on the measured signals.

Four turbine shut-downs studied have in common that they happened in connection with an increase in wind speed or wind gradient. One half to one minute passed since the last yawing, although the simulations demanded several more yawings. An increase of the teetering motion caused shut-down due to large vertical or horizontal teeter angles. There is, however, no clear explanation of these teeter excursions.

3.3.6.4 Tests with the turbine directed out of the wind

Limited tests were performed with the turbine intentionally directed out of the wind direction during stall and below stall conditions. The results reveal that minimum horizontal teeter angle was obtained when the turbine is yawed 10^{o} anti-clockwise from the wind direction indicated. The mean value of the vertical teeter angle was not effected of the yawing, however, there was some indication that the maximum vertical teeter excursions decreased when the turbine was yawed clockwise.

3.3.6.5 Influence of stall strips and blade pitch on the vertical teeter angle

As noted under 3.2.2.4, stall strips were installed on the blades and the blade pitch settings were varied. One of the objectives for these experiments were to investigate whether it is possible to achieve less teeter excursions in this way.

In the first set up the blade pitch setting was -2,2/-1,7° and in the second -0.8°. The amount of stall strips was 0,8 and 3,0 m respectively.

The results demonstrate some decrease (0,1-0,5°) of the maximum vertical teeter angle. The effect was, however, less pronounced than expected.

3.3.6.5 Simulations

The following results were obtained from the Vidyn-simulations:

- For a teetered hub without teeter spring, a 6° tilt, as on the NWP 400 machine, generates large teeter angles (8°) in stall conditions, even without wind shear or yaw misalignment.
- A 700 kNm/rad teeter spring, as on the NWP 400, reduces the teeter angle in combination with a 10° yaw misalignment to around 5,5°. Wind shear has less implication.
- When in combination with stall aerodynamics (Beddoes model), the teeter angle in the preceding case increases to 7° and the phase angle to 85/195°, depending on direction of misalignment.
- An increase of the teeter spring to 1000 kNm/rad reduces the teeter angles with about 1°.
- The smallest vertical teeter angles are achieved by applying a slight clockwise misalignment that will reduce the extreme teeter excursions.
- Adding a hydraulic coupling to the yaw drive decreases the teeter angles and makes the wind turbine able to operate also during extreme load cases.
- Parts of the results indicate that the aerodynamic stability is at a minimum at around 15 m/s, which triggers oscillations in the teeter angle. This makes the teetering sensitive to extremes and odd situations, which may be created by the wind and by the yawing system.

3.3.6.7 Conclusions

At wind speeds exceeding about 13 m/s, the teeter angle increases and the phase angle stabilises. The wind turbine is frequently shut down due to large teeter angles at high wind speeds. Shut-downs studied have in common that they happened in connection with an increase in wind speed or wind gradient, but not in connection with yawing, although simulations indicate that yawing was justified. Results from the analysis indicate that there are several ways of reducing the teeter angles to such an extent that shut downs will become less frequent than today.

3.4 ELECTRICAL CHARACTERISTICS

3.4.1 Introduction

The objective of this chapter is to present the result of the electrical measurements of the power quality at the site of Lyse Wind power station. The measurements and evaluations are made as far as possible according to the document IEA Recommended Practices for Wind Turbine Testing and Evaluation, 1st edition 1984.

Measurements were also performed 1992 and 1993 in order to study the harmonic content of the output from NWP 400. They showed a THD in voltage of 3% on the high voltage side. On the low voltage side the corresponding value was 7%. This was considered to be to high and a filter was mounted on the NWP machine, this reduced the THD to 4% which was considered acceptable.

3.4.2 Measuring conditions

The measurement was performed in the substation at Lyse during the period 4 April 1995 to 22 June 1995.

The testing was performed with the following instruments rented from Vattenfall Utveckling AB: For the long term registrations of voltage dips and interruptions an instrument from Dranetz, model 656, was used. Flicker and harmonics were measured with an instrument from RST, model Transan-16, and finally inrush parameters with an instrument from Dranetz, model PP1.

The measurements were mainly made at the Point of Common Coupling (PCC) on the high voltage side of the transformer T2 at point H2, see figure 3.4:12 The voltage transformer T2-10-UT and the current transformer T2-10-IT were used. Measurements were also made on the low voltage side of the transformer using current transformer T2-0,7-IT and voltage directly on the busbar of the transformer. Currents from NWP were also registered with clamp on transformers on the cable from the generator.

The frequency responses from the current and voltage transformers were not checked and this may cause a minor error in the registrations of harmonics of higher order.

Transformer T2 has the following data: Rated power 1 MVA, ratio 10,5/0,693 kV, Δ/Yn.

3.4.3 Current and voltage harmonics

Harmonics have been measured at different wind speed conditions. The registrations, at least for two hours, were performed on one unit at a time with the other unit stopped from Trollhättan control centre. Registrations without WECS were performed with breaker TK51-S and TK52-S open.

The registrations have been performed according to applicable parts of IEC 1000-4-7 with the exception that the registration time has been reduced to two hours because disconnecting of one unit for more than two hours was not permitted.

In following diagrams each 95%-value of the harmonics have been plotted vs. harmonic number (n*50 Hz). The 95%-value is the value which, with 95% probability is not exceeded during the measuring period. Under low load conditions it is meaningless to calculate the total harmonic distortion and percentage for the harmonics because this often give high percentage values also when the harmonic current is still very small and mostly harmless to the network. Also Vattenfall's internally proposed limits for harmonics in medium voltage power systems are plotted in the same diagram.

Arithmetic as well as vectorial calculation of the harmonics have been made and the difference between these methods are at Lyse very small (at most some tenth of a percent).

In following tables the median, 95%, 99% and the mean values of the measured parameter are printed for the fundamental, the RMS and the total harmonic distortion. For currents also the total demand distortion, which is an fictive value of interest, have been calculated.

The relative harmonics content is the relation between the effective value of each harmonic and the effective value of the fundamental taken from the same curve shape. For voltage $U_n/U_1 \cdot 100$ % and for current $I_n/I_1 \cdot 100$ %.

The total harmonic distortion THD is calculated as follows

$$THD_I = 100 \cdot \sqrt{\sum_{n=2}^{\infty} (\frac{I_n}{I_1})^2} \,\% \quad \text{resp} \quad THD_u = 100 \cdot \sqrt{\sum_{n=2}^{\infty} (\frac{U_n}{U_1})^2} \,\%$$

3.4.4 Measured line voltages at PCC

3.4.4.1 Harmonics without WECS connected

The measurement was performed 16 June 1995 between 11:00 and 13:30 on the high voltage side of the system transformer. The circuit breakers TK51 and TK52 were open. The highest value was recorded between phase R and T.

U	Median	95%	99%	Mean	Unit
U_1 (fund)	10,53	10,63	10,63	10,54	kV
U_{rms}	10,53	10,63	10,64	10,54	kV
THD_U	0,66	1,10	1,12	0,73	%

Table 3.4:1. Line voltage between phase R and T

Highest registered harmonic was the 5th, just above 1%.

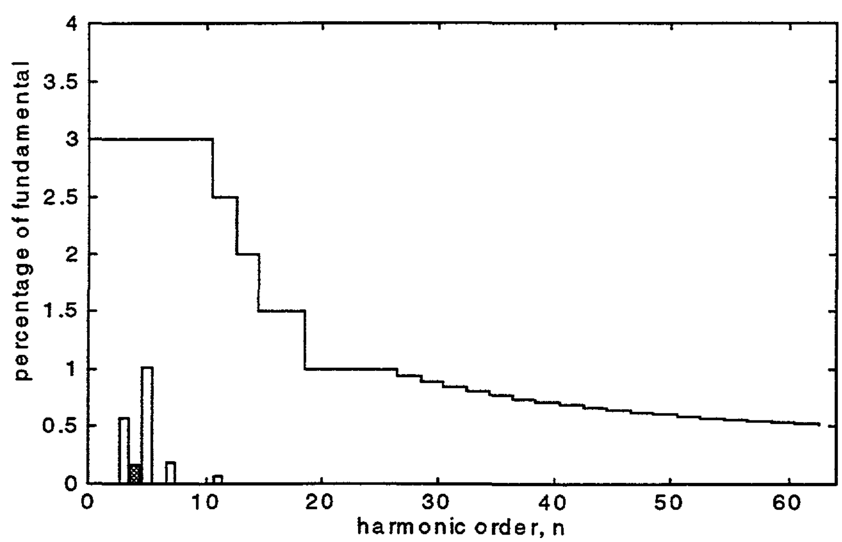


Figure 3.4:1. PCC - harmonics in voltage, background

3.4.4.2 Voltage harmonics with NWP400 operating near rated power
The measurement was performed 19 June 1995 between 07:32 and 10:03 on the high voltage side of the system transformer. The highest value was recorded between phase S and T.

U	Median	95%	99%	Mean value	Unit
U_1 (fund)	10,50	10,55	10,55	10,49	kV
U_{rms}	10,50	10,55	10,55	10,50	kV
THD_U	1,1	1,4	1,4	1,1	%

Table 3.4:2 Line voltage between phase S and T

Highest registered harmonic was the 35th, just above 0,7%.

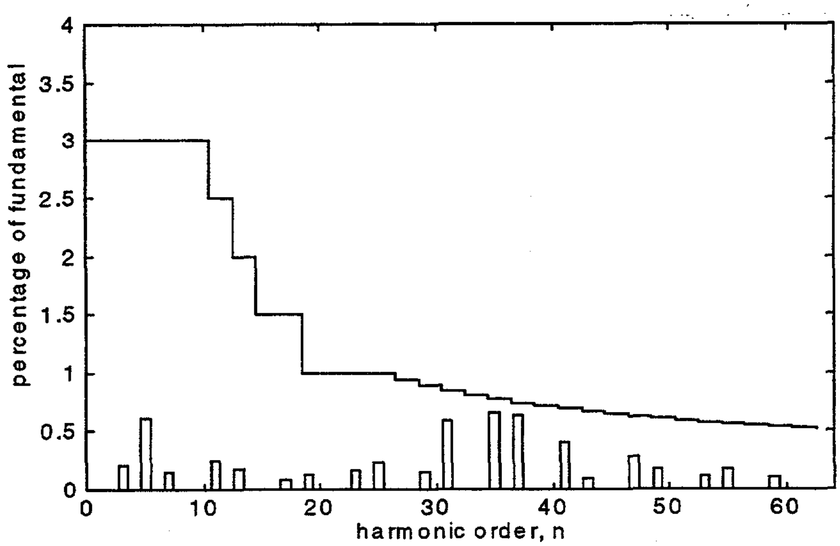


Figure 3.4:2 NWP - harmonics in voltage

3.4.4.3 Voltage harmonics with NWP400 operating at minimum power
The measurement was performed 16 June 1995 between 08:25 and 10:46 on the high voltage side of the system transformer. The highest value was recorded between phase S and T.

U	Median	95%	99%	Mean value	Unit
U_1 (fund)	10,43	10,46	10,46	10,43	kV
U_{rms}	10,43	10,46	10,46	10,43	kV
THD_U	1,6	1,8	1,8	1,2	%

Table 3.4:3 Line voltage between phase S and T

Highest registered harmonic was the 37th, just above 1,0%.

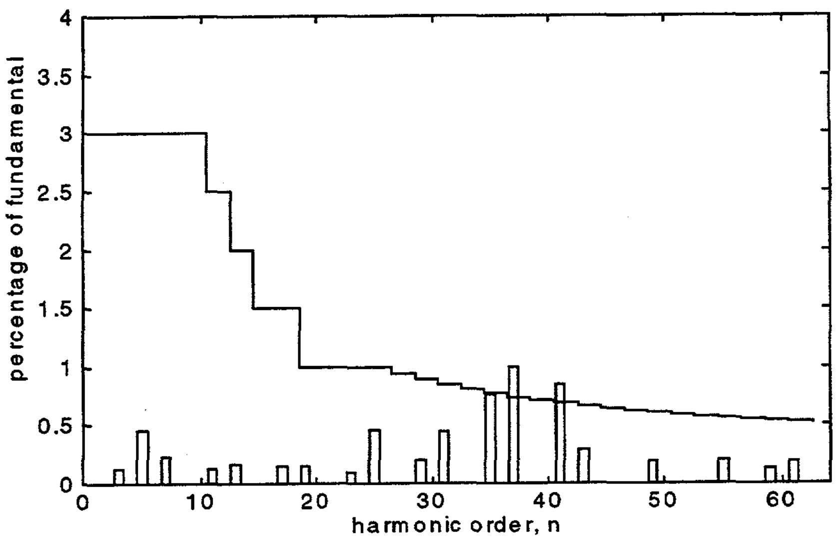


Figure 3.4:3 NWP 400 - harmonics in voltage

3.4.4.4 Voltage harmonics with Bonus operating near rated power
The measurement was performed 19 June 1995 between 12:51 and 14:54 on the high voltage side of the system transformer. The highest value was recorded between phase R and T.

U	Median	95%	99%	Mean value	Unit
U_1 (fund)	10,61	10,66	10,68	10,61	kV
U_{rms}	10,61	10,66	10,68	10,61	kV
THD_U	0,68	0,79	0,81	0,67	%

Table 3.4:4 Line voltage between phase R and T

Highest registered harmonic was 5th, just above 0,7%.

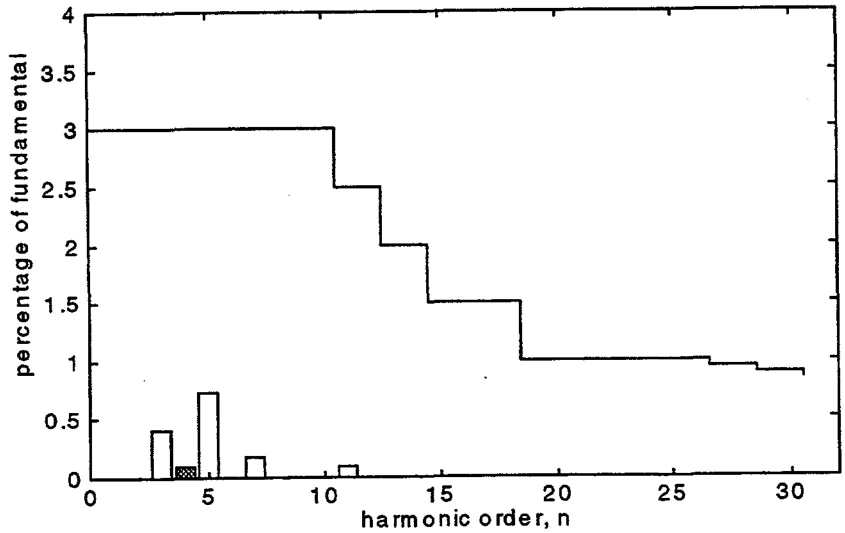


Figure 3.4:4 Bonus 450 MkII - harmonics in voltage

3.4.5 Measured currents at PCC

Measurements of current harmonics were performed the same way as for voltage, however presenting THD or single harmonics as a percentage of fundamental current may give very high values in case of minimum output. The harmonic current may in this case be very low and does not effect the grid very much. A better method may be to calculate TDD (total demand distortion) wich is done in the minimum load case at Lyse.

$$TDD_I = 100 \cdot \sqrt{\sum_{n=2}^{\infty} \left(\frac{I_n}{I_{demand}}\right)^2} \ \% ,$$

where I_{demand} is the maximum load current in the measuring point measured during a longer period of time. In this report the value for I_{demand} was set to 50A for PCC at Lyse.

3.4.5.1 Current harmonics with NWP 400 operating near rated power

The measurement was performed 19 June 1995 between 07:32 and 10:03 on the high voltage side of the system transformer. The highest value was recorded in phase T.

I	Median	95%	99%	Mean value	Unit
I_1 (fund)	16,4	17,0	17,2	16,3	A
I_{rms}	16,5	17,1	17,2	16,4	A
THD_I	5,3	6,1	6,5	5,4	%
$TDD_{I\,(50A)}$	1,8	2,1	2,2	1,8	%

Table 3.4:5 Current in phase T

Highest registered harmonic was the 13th, just less than 3% which is 0,5A.

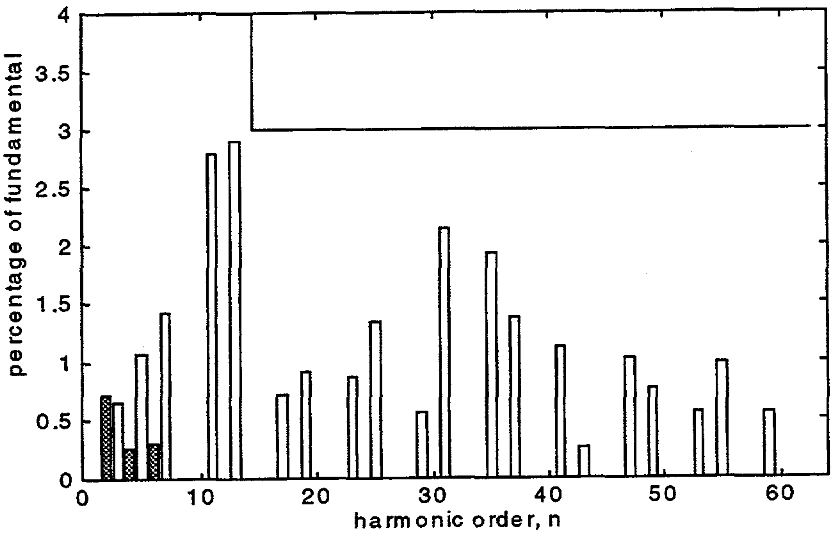


Figure 3.4:5 NWP 400 - harmonics in current phase T

3.4.5.2 Current harmonics with NWP400 operating at minimum power
The measurement was performed 16 June 1995 between 08:25 and 10:46 on the high voltage side of the system transformer. The highest value was recorded between phase T.

I	Median	95%	99%	Mean value	Unit
I_1 (fund)	0,51	0,80	0,88	0,52	A
I_{rms}	1,26	1,43	1,50	1,01	A
$TDD_{I\,(50A)}$	1,8	3,9	4,5	1,5	%

Table 3.4:6 Current in phase T

Highest registered harmonic was the 11th, 0,5A.

3.4.5.3 Current harmonics with Bonus 450 MkII operating near rated power
The measurement was performed 19 June 1995 between 12:51 and 14:54 on the high voltage side of the system transformer. The highest value was recorded in phase R.

I	Median	95%	99%	Mean value	Unit
I_1 (fund)	18,1	21,8	22,6	18,1	A
I_{rms}	18,1	21,8	22,6	18,1	A
THD_I	1,4	1,9	2,1	1,4	%
$TDD_{I\,(50A)}$	0,5	0,8	0,9	0,5	%

Table 3.4:7 Current in phase R

Highest registered harmonic was the 11th, just less than 1% which is 0,2A.

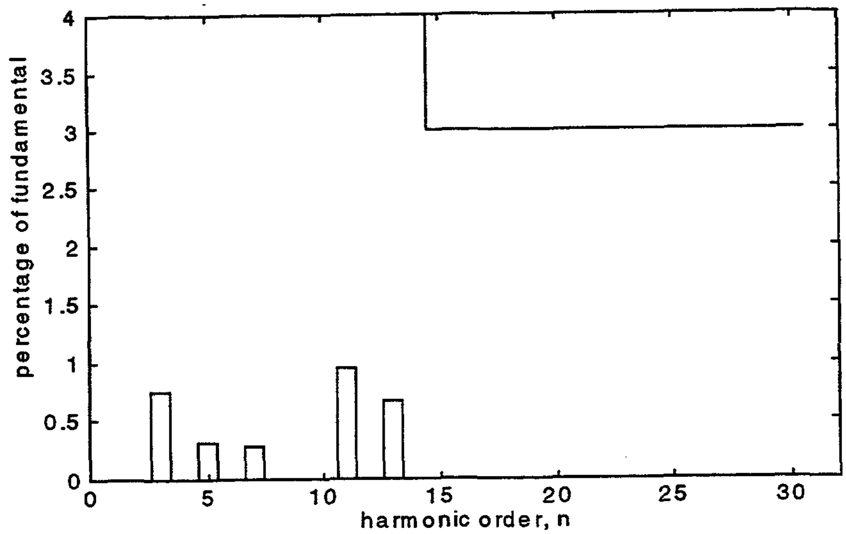


Figure 3.4:6 Bonus - harmonics in current phase T

3.4.6 Measurement of current and voltage during connection and disconnection of the units to the grid.

Registrations of currents and voltages during connection and disconnection of the WEC to the grid measured at PCC were made at several repetitive times at a power production of 350 kW (wind direction 60°) on each unit. Only the unit under test was operating while the other was disconnected from the grid.

3.4.6.1 Connection of NWP to the grid

The following figure shows the current in phase R during connection to the grid measured at PCC (high voltage side of system transformer). At time 100s in the figure the unit produce power to the grid. The operation does not effect the peak or the effective value of the voltage.

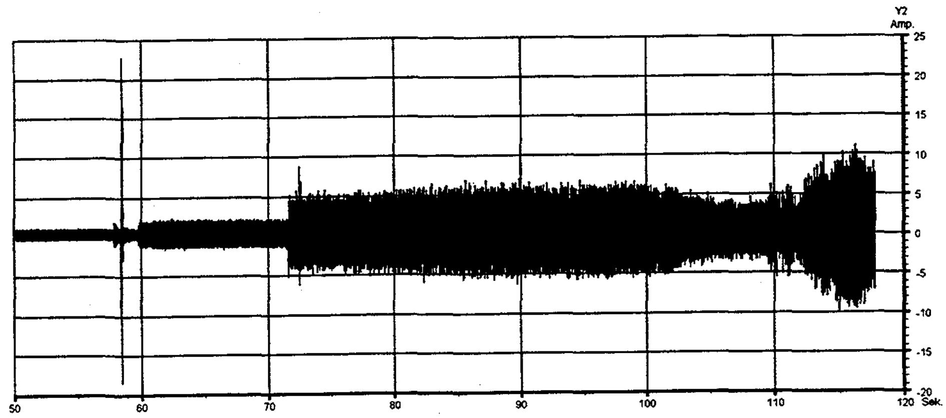


Figure 3.4:7 Current in phase R during connection to the grid of NWP400.

3.4.6.2 Disconnection of NWP from the grid

The following figure shows the effective value of the current and voltage in phase R during disconnection of NWP400 from the grid. The power production in the unit was 330 kW just before operation of the breaker. At 40s in the time scale the unit consume power from the grid.

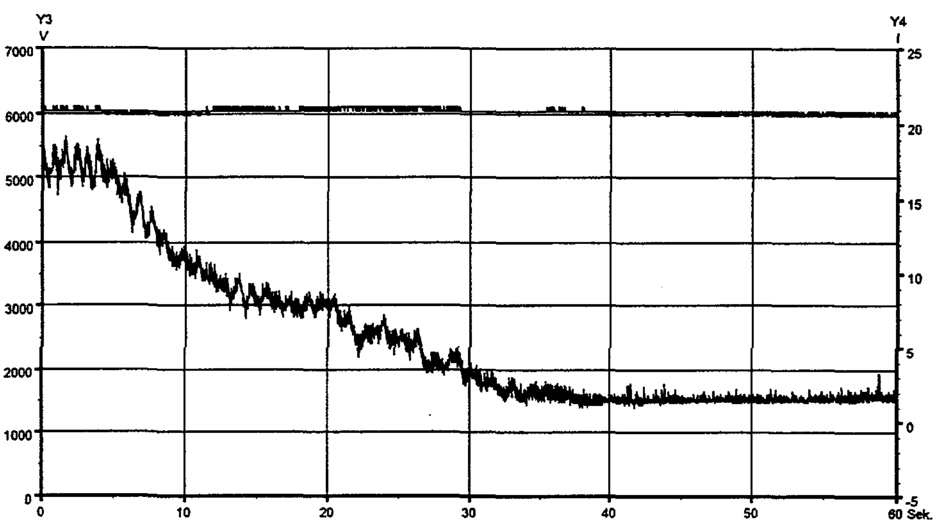


Figure 3.4:8 Current and voltage during disconnection of NWP400

3.4.6.3 Connection of Bonus to the grid

The following figures shows the current and voltage in phase T during connection to the grid measured at PCC (high voltage side of system transformer). At time 4s of the figure the unit begins to produce power to the grid. The voltage dip is about 3% and will cause flicker.

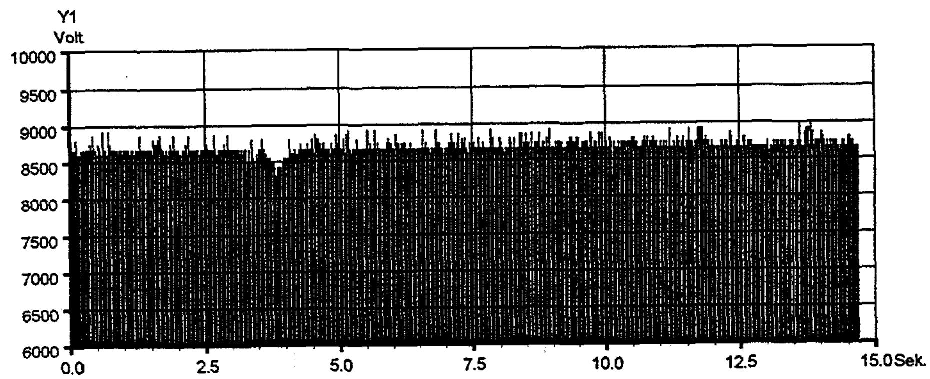


Figure 3.4:9 Voltage in phase T during connection of Bonus

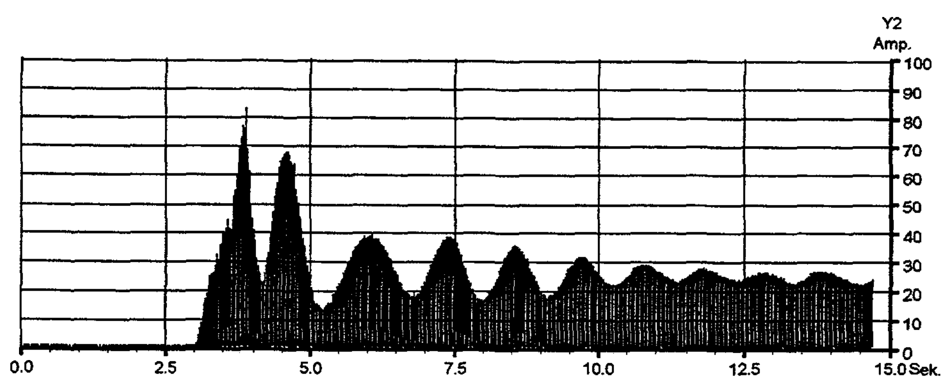


Figure 3.4:10 Current in phase T, positiv halfperiod, during connection of Bonus to the grid

3.4.6.4 Disconnection of Bonus from the grid

The following figure shows the wave form of the current and voltage in phase R during disconnection of Bonus from the grid.

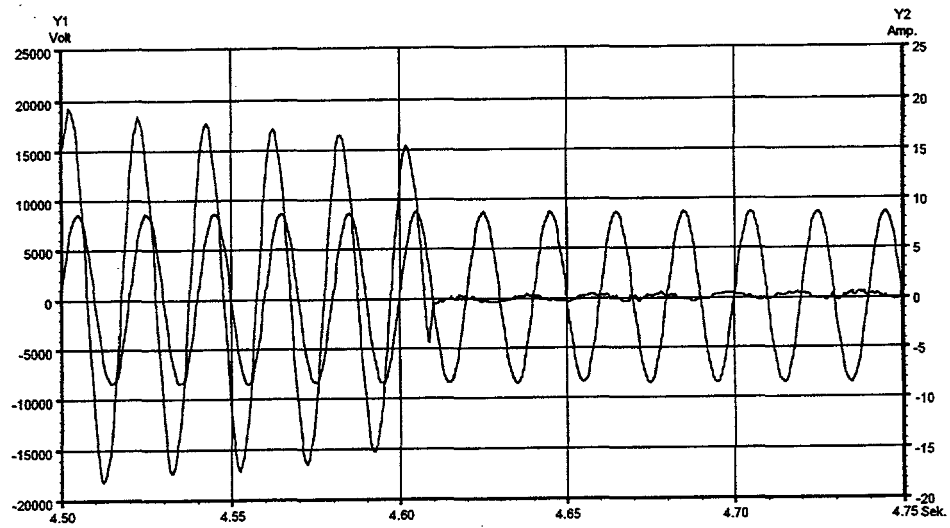


Figure 3.4:11 Current and voltage wave form at disconnection of Bonus from the grid

3.4.7 Long term registration of voltage in PCC

Voltage dips and short interruptions are among the most annoying disturbances, affecting the voltage quality of the network. The purpose was to obtain information of disturbances at PCC by means of registration under a longer time. The registrations were performed under 40 days at different periods from 10 April 1995 to 19 June 1995. The registration and evaluation of dips were made according to UIE.

Several voltage dips occurred during the registration time and also an interruption (14 minutes) occurred. These faults originated from the network and not from the WECS.

In the following table the number of events are counted in each cell for all phases according to UIE. The voltage must return to a value of at least 90% of nominal voltage before a new dip will be counted.

The nominal voltage at PCC is 10,6 kV and voltage dip of 10% will reduce the voltage to 9,54 kV for at least 10 ms.

Dip (Δu/u%)	Duration (Δt)						
	Half a cycle to <100 ms	100 ms to <500 ms	500 ms to <1s	1s to <3s	3s to <20s	20s to <60s	60s to <90s
10 to <30	5	4		1			
30 to <60	1	2					
60 to <100		4				3	
100							

Table 3.4:8 Maximum number of events in all phases at site

3.4.8 Rapid voltage changes - flicker

During the period 26 April 1995 to 5 March 1995 flicker was registered at PCC. Flicker is the subjective impression of voltage fluctuations in a voltage feeding a lamp bulb. The severity of flicker depends on how the eye and brain interpret the light variations. The registrations were performed according to IEC's and CIGRÉ's recommendations, with one exception: The presented values are rolled P_{st}-values (were st means "short time severity") which means that P_{st} is calculated from ten 1-minute values and every minute the oldest 1-minute value is replaced with next new value. This method gives a new P_{st}-value every minute instead of one consecutive P_{st}-value every 10 minute.

The P_{st}-value is produced by the flicker meter. The $P_{st.95\%}$-value for the whole measurement shall be compared with the target limits. The $P_{st95\%}$-value is the value which is not exceeded during 95% of the time. Another presented value is $P_{st.3max}$ which is the third highest P_{st}-value during the measuring period.

Both units, NWP400 and Bonus, have been operating during the registration time.

In following table the highest $P_{st95\%}$-value and $P_{st.3max}$-value in the three phases is compared to the target limits proposed as "Planning Limits" by IEC 77A. 08 TF-ICU.

Measuring point	Measured value [$P_{st.95\%}$]	Proposed target limits 1)	$P_{st.3max}$
10 kV	0,24	1,0	0,73
0,7 kV	0,25	1,0	0,96

1) "Planning Limits" proposed by IEC 77A. 08 TF-IC.

Table 3.4:9 Flicker levels

3.4.9 Power variations and reactive power demand

Assessment of power variations and the reactive power demand as well as determining the power curve were carried out during the same period of time by the regular measuring system installed in the plants. The evaluation follows chapter 4.2 and 4.3.1 in IEA. The result is reported in FFA's test report.

3.4.10 Conclusion

The registrations of currents and voltages at PCC at Lyse Wind Power Station regarding power quality characteristics show a minor influence on the network. The registrations were carried out on the high voltage side (10 kV) of transformer T2 except the power variations and reactive power demand which were carried out on the low voltage side (0,7 kV) and are measured with the plant's ordinary measuring system described earlier in this report.

Only two of the registered harmonics (95%-values) exceeded Vattenfall's internal recommendations for maximum allowed harmonic content, which are practised due to lack of standards. The two harmonics did not exceed the limits much and were registered when NWP was running at low power.

The registered flicker levels was low, partially because of the low wind speed during most of the measuring time. In this case it could be better to pay attention to the $P_{st.3max}$ instead.

The long term registrations of voltages in PCC show a relatively high occurrence of voltage dips. However most of the dips were related to four major occurrences. One total voltage collapse occurred during the registration time. The units have been stopped and started a large number of times. The registered faults which did not origin from the two units, was related to the 10 kV-network.

Registrations of currents and voltages when the units were connected or disconnected to the network are presented by diagrams in the report. The largest voltage dip (3%) was registered when Bonus was connected. Dips of this magnitude causes flicker. The connection of NWP caused a current peak (one period) which could probably be related to the inverter. Generally the performed measurements show a small impact on the network.

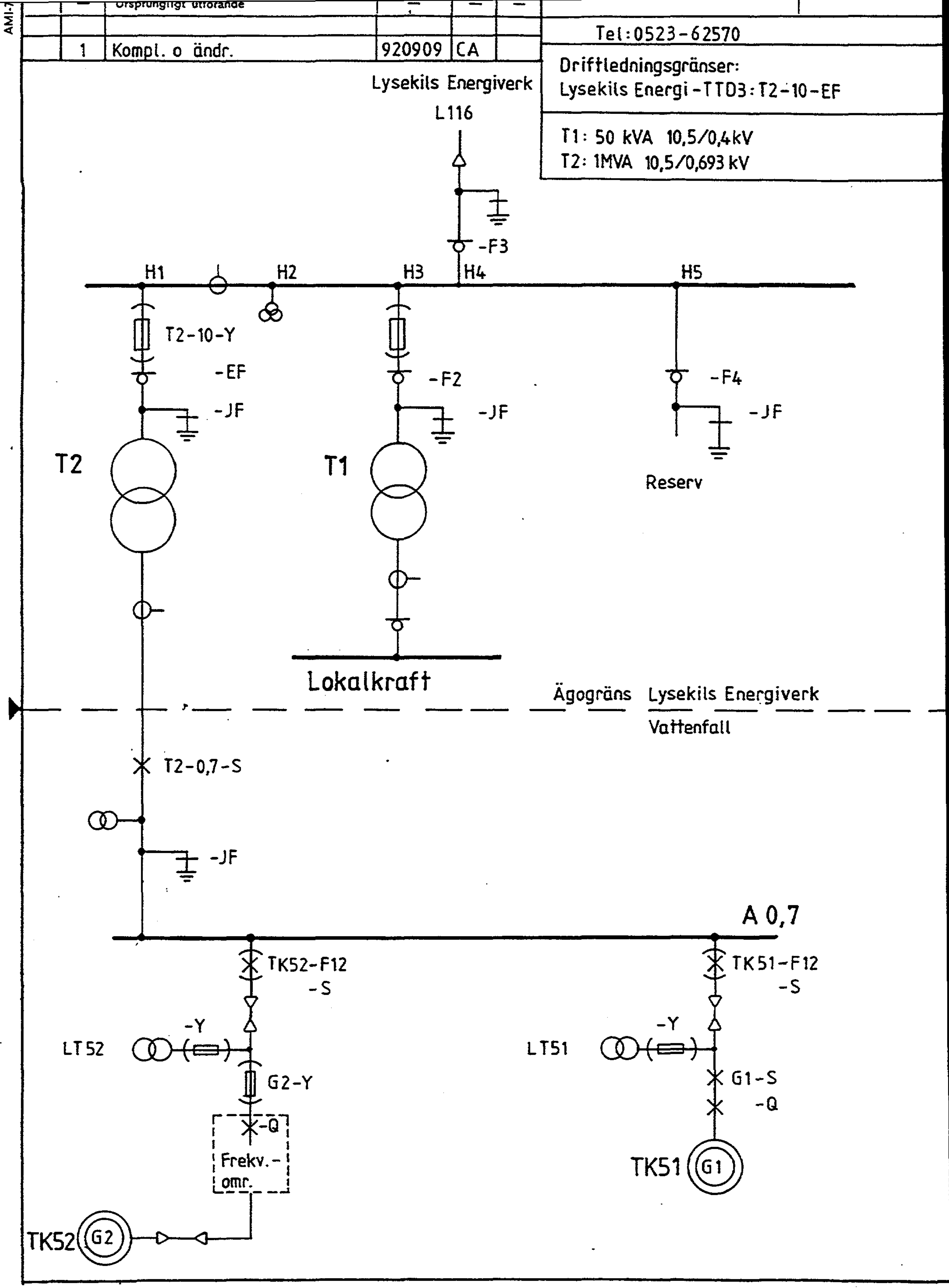


Figure 3.4:12 Electrical connections

3.5 CONTROL SYSTEM PERFORMANCE

In the following pages the control system performance of the NWP 400 will be discussed. This chapter contains a number of tables and Figures. The acronyms of the different variables shown in the Figures can be seen in the list below.

AERODYNAMICS

WS	wind speed	
Lambda, λ	tip speed/wind speed = RS*R/WS	
R	turbine radius	
CQ	torque coefficient	
DCQ	derivative of CQ with respect to λ	

TURBINE

RS	rotor speed	
JB	blade inertia	
JH	hub inertia	
JT	total turbine inertia	JT=2*JB+JH
KB	blade stiffness	
DB	blade damping	
ωB	blade resonance	
RTORA	aerodynamic torque	

DRIVE-TRAIN

N	gear ratio
GS	generator speed
JG	generator inertia
KS	shaft stiffness
ωG	drive-train resonance
DS	shaft damping
RTORS	shaft torque
GTORE	electrical torque
GTEREF	reference value

CONTROL

Ka	loop gain
T	time constant

MEASUREMENTS

WS48	wind speed
GS	generator speed
WTAP2	active power
1p 2p 4p 6p -	variations, 1p means same frequency as turbine speed, 2p double frequency etc.

3.5.1 Analysis

3.5.1.1 Background and aerodynamics

The behaviour is very dependent on wind speed. It is therefore appropriate to define three different wind speed ranges where the circumstances are similar. This is evident from the LT-diagram, Figure 3.5:2. At low wind speed the machine follows the optimal-λ line. At higher wind speed when the maximum allowed speed is reached the speed control starts. First comes an intermediate region where torque varies strongly with wind speed (the constant torque lines Q are rather vertical) and at still higher wind speed the stall region is reached where the torque varies much less (the constant torque lines are more horizontal).

Some measurements of the aerodynamics have been performed on a limited basis. Different configurations (blade angles, stall strips) have been tested. Figure 3.5:1 shows the power curve (power delivered to the grid). For configuration B and F are $C_p(\lambda)$-values calculated. These values are used for simulations. Especially configuration F has very low maximum power.

The general goal was to estimate:

- Control qualities at different wind speeds.
- The behaviour of the drive-train and generator with torque control.
- Disturbances.

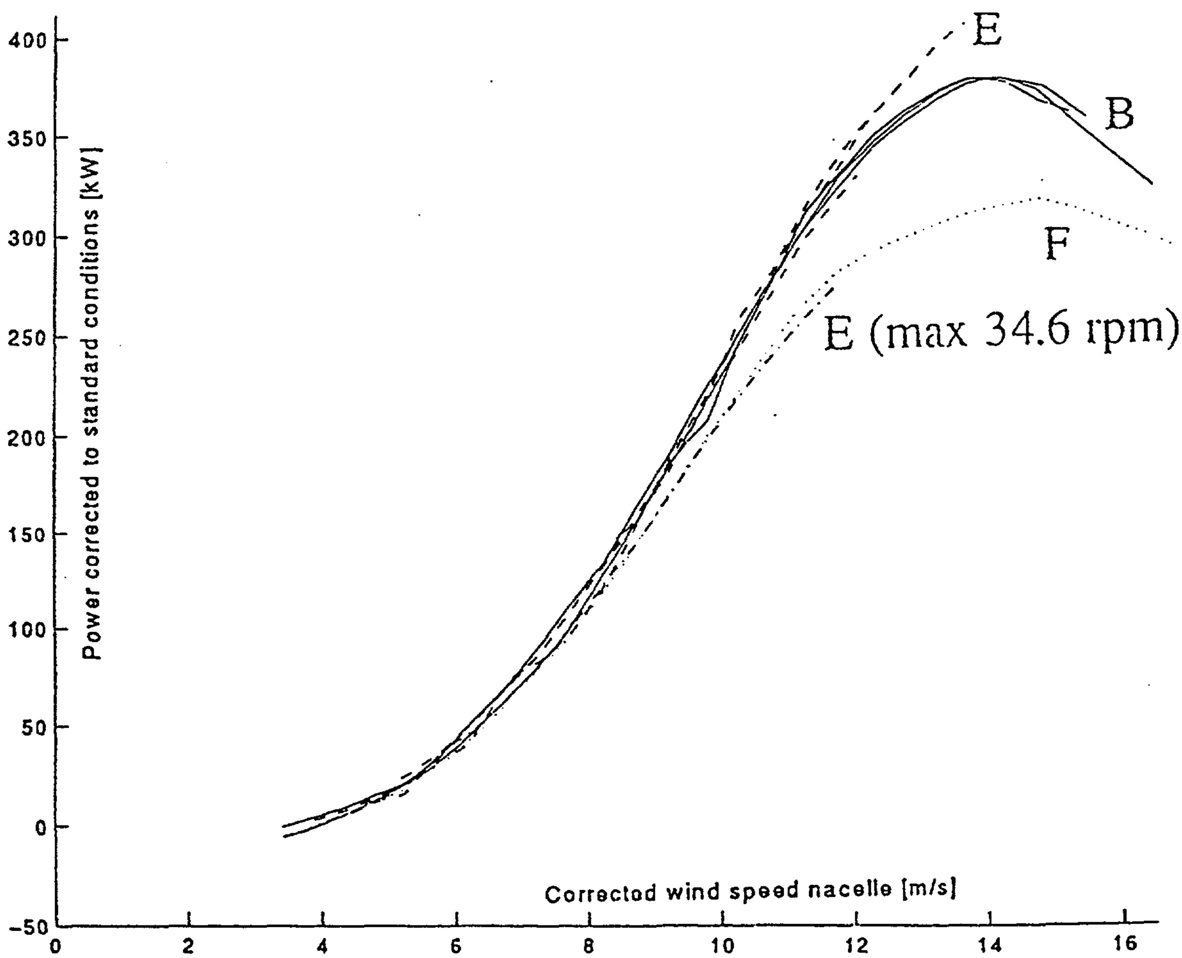


Figure 3.5:1 Power curve. Two blade configurations:

B Blade angle-2.2 and -1.7. First arrangement of stall strips
E Blade angle -0.8 both blades. First arrangement of stall strips
F Blade angle -0.8 both blades. Second arrangement of stall strips

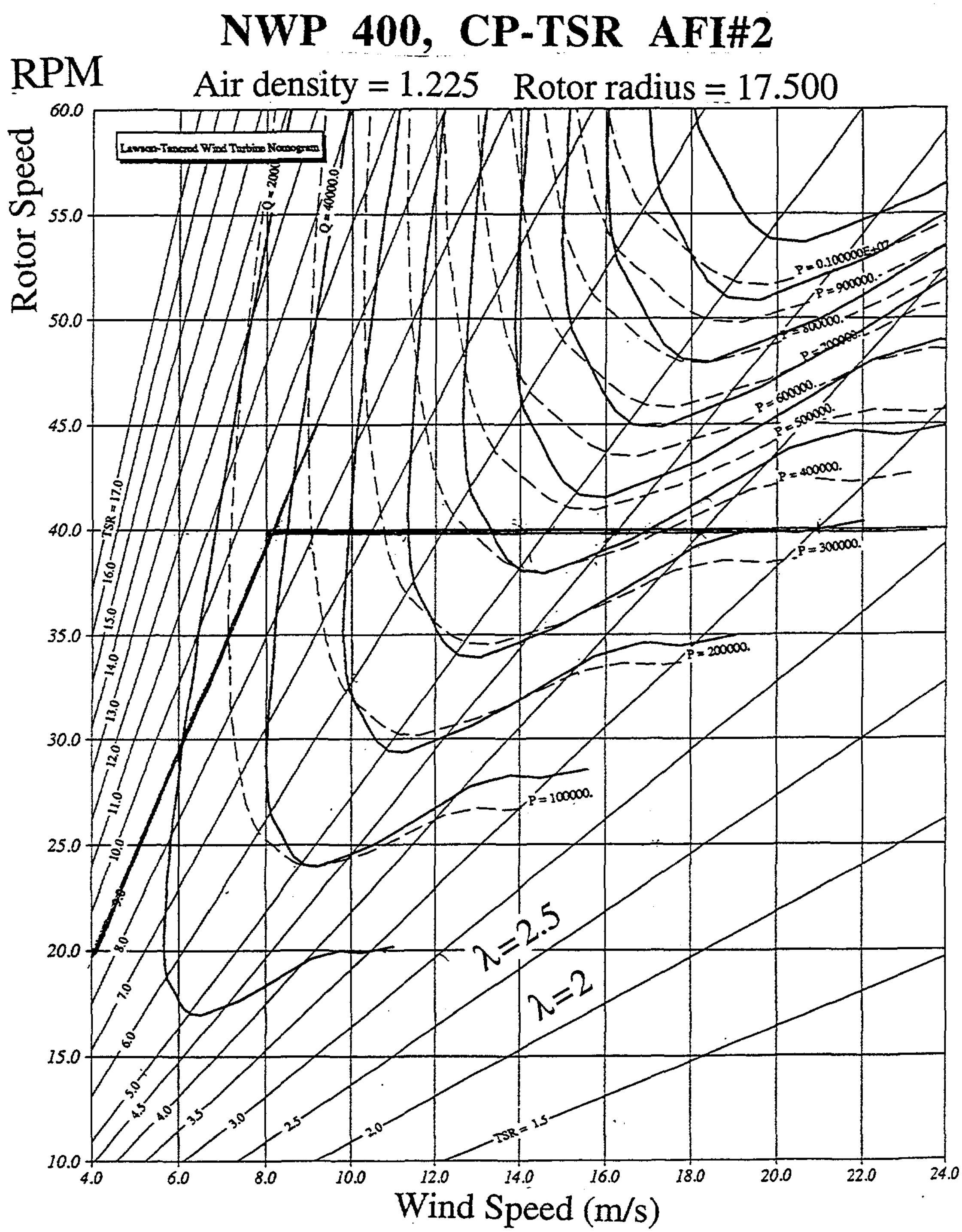


Figure 3.5:2 LT-diagram.

Three modes of operation:

- Optimal WS < 9 m/s
- Second 9 < WS < 14 m/s
- Stall 14 < WS < 24

Q = aerodynamic torque
P = rotor active power

3.5.1.2 Drive-train

A model with three inertias is supposed

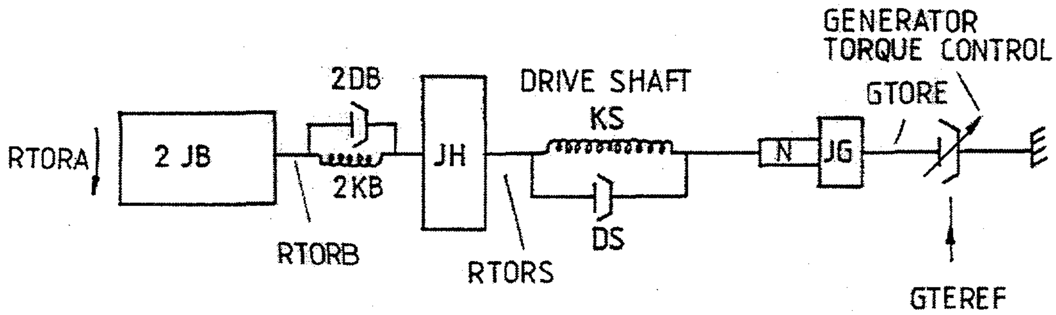


Figure 3.5:3 Drive-train model

Two resonances can be distinguished in the following called blade resonance ωB (S mode) and drive-train resonance ωG.

FREQUENCIES < THE LOWEST RESONANCE (stiff system)

The following transfer functions can easily be calculated

$$\frac{RTORS}{RTORA} = \frac{JGS}{JT + JGS} \approx \frac{JGS}{JT} \text{ if } JGS << JT$$

$$JGS = N^2 * JG$$

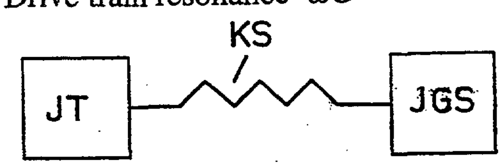
$$\frac{RTORS}{N * GTORE} = \frac{JT}{JT + JGS} \approx 1 \text{ if } -"-$$

As JGS << 2JB + JH = JT a strong damping of disturbances is obtained.

FREQUENCIES ≥ THE LOWEST RESONANCE

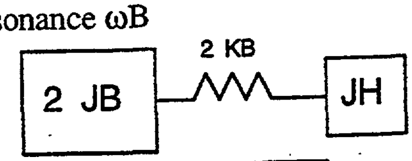
If the blade resonance is considerably greater than the drive-train resonance they can approximately be treated separately.

(1) Drive train resonance ωG



$$\omega G = \sqrt{\frac{KS}{\frac{JGS \cdot JT}{JGS + JT}}} \sim \sqrt{\frac{KS}{JGS}} \quad (JGS << JT)$$

(2) Blade resonance ωB



$$\omega B = \sqrt{\frac{KB}{\frac{JB \cdot JH}{2JB + JH}}}$$

A more precise result can be obtained through calculating the poles of the complete system or to establish frequency diagram. Especially the blade resonance is dependent on the distribution of the inertias between blade and hub. A quantity α is defined:

$$JB = JT(1-\alpha); \quad JH = JT * \alpha$$

The following diagram shows how the different resonance frequencies and relative damping depends on KB and α.

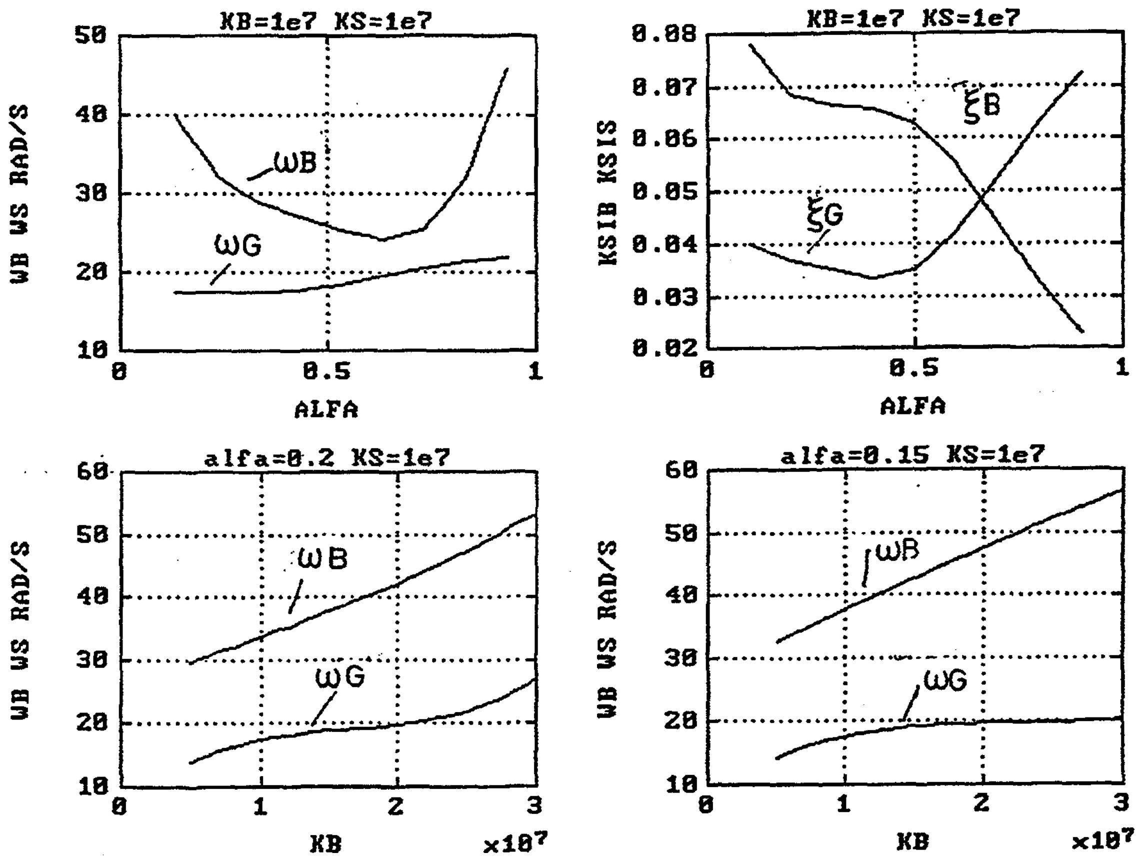


Figure 3.5:4 Resonance dependence on α and KB

The following values have been adopted as nominal.

TURBINE

$\alpha = 0.15$
JT=2JB+JH=170000
JB=72250
JH=25500
KB=1E7
DB=13200

Gives ωB= 30.4 and KSIB= 0.02
in the separated case

DRIVE-TRAIN AND GENERATOR

N =40
JG=15
KS=1E7
DS=68800

Gives = ωG=21.8 and KSIG= 0.075
in the separated case

The following diagram shows the drive-train sensibility to disturbances from the turbine side (aerodynamic disturbances) and generator side. The relative damping of the resonances is difficult to estimate. It appears from the diagram that when disregarding the drive-train resonance a strong damping of disturbances from the turbine side is obtained. No such damping is obtained from the generator side. However, more or less damping of the drive-train resonance is obtained through the speed control, which will be treated later on.

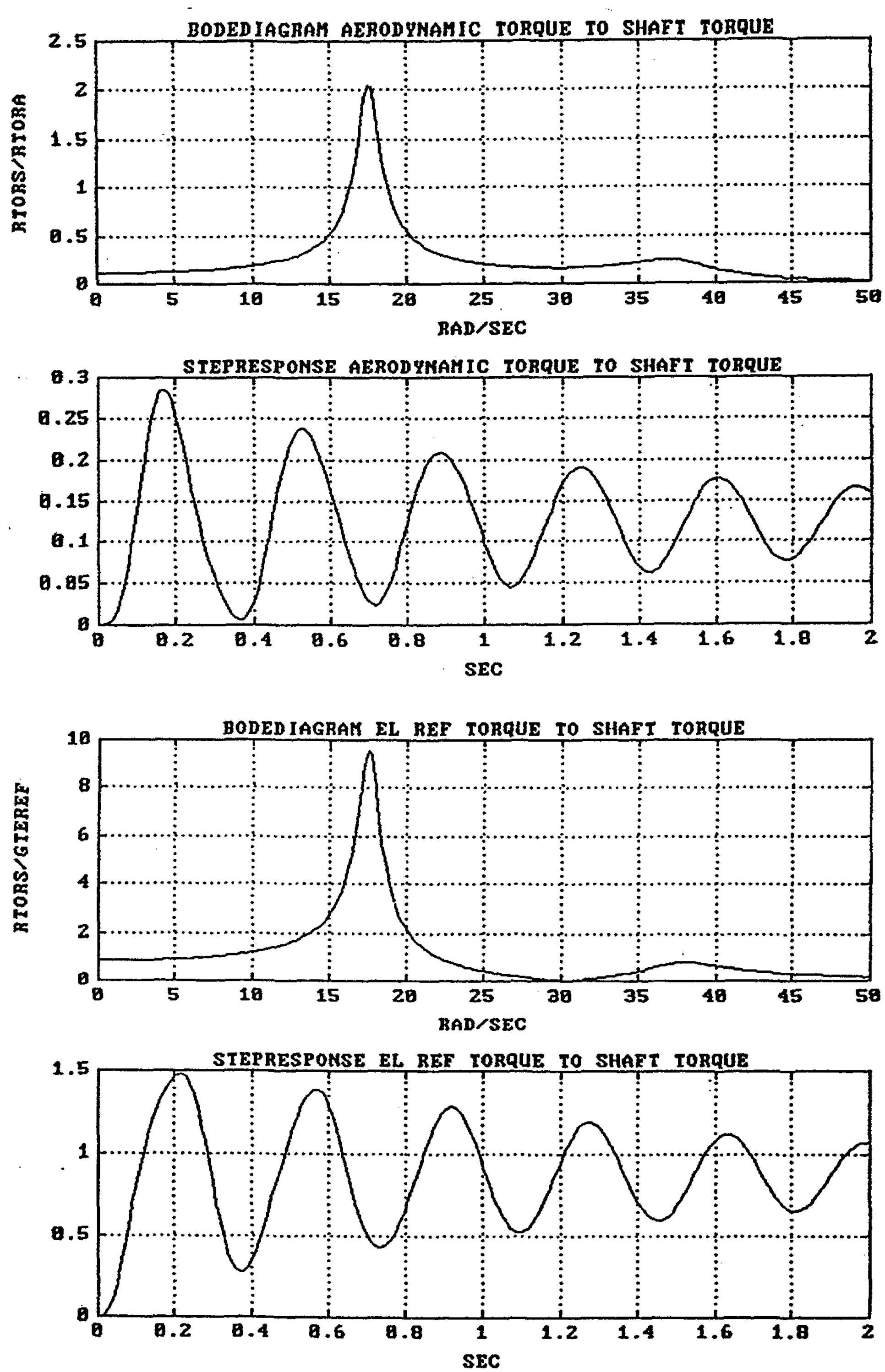


Figure 3.5:5 Sensibility to disturbances

3.5.1.3 Control

TURBINES

The following diagram shows the torque coefficient CQ and the derivative of CQ with respect to λ designated DCQ.

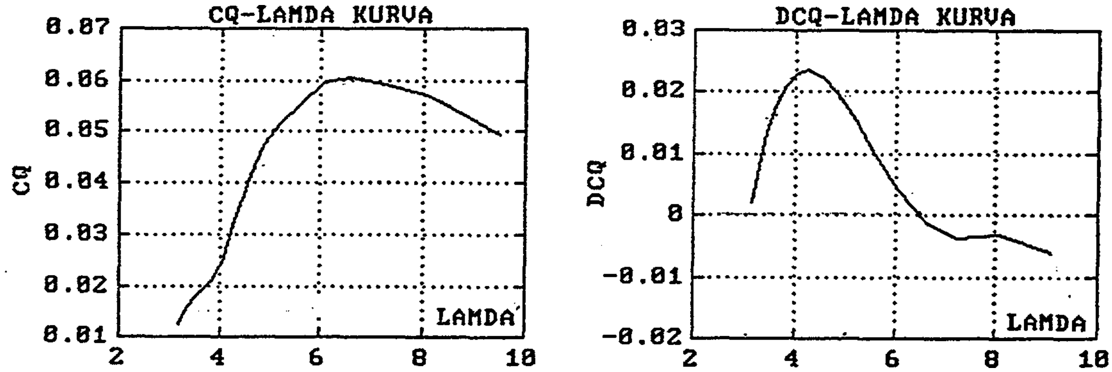


Figure 3.5:6 CQ(λ) and DCQ as function of λ

$\lambda > 6.5$ DCQ negative and constant.

In this case the integration between torque and speed is changed to a wind dependant time constant TRS depicted in the following diagram.

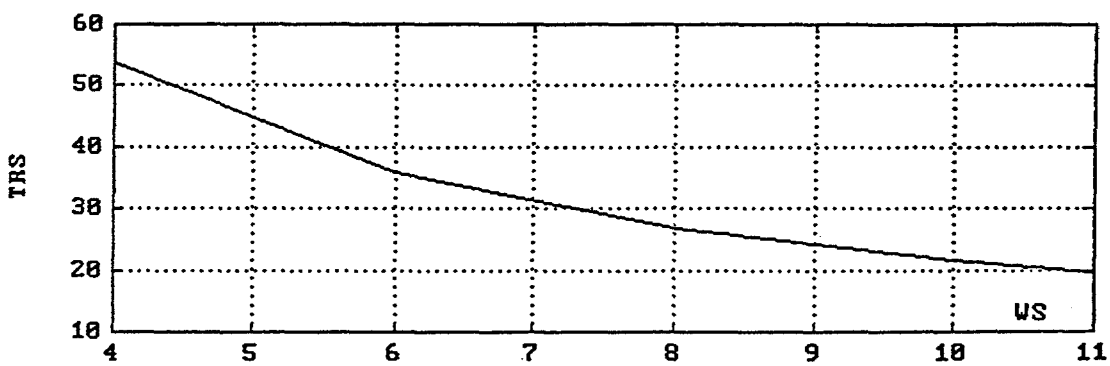


Figure 3.5:7 TRS as function of WS

$\lambda < 6.5$ DCQ positive and the turbine is unstable without control.

There will be a phase shift at low frequencies depicted in the following diagram for the most severe case.

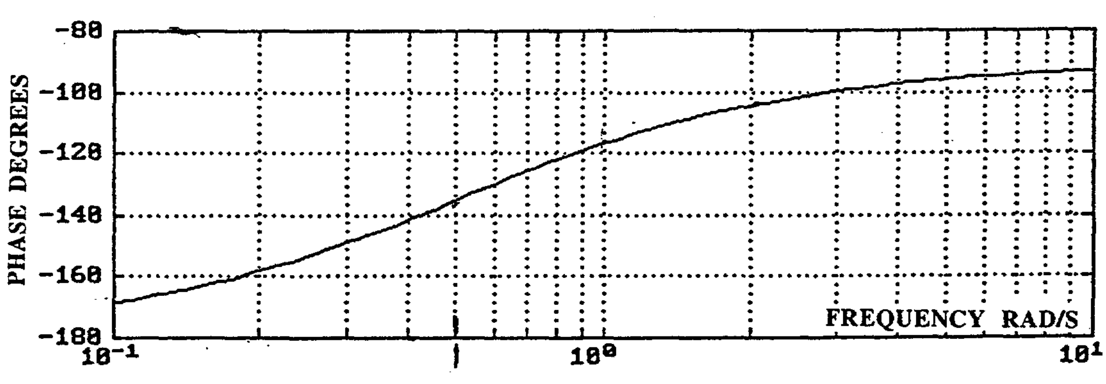


Figure 3.5:8 Phase shift at low frequencies

SPEED CONTROL

The following diagram shows the control scheme with the actual scaling included.

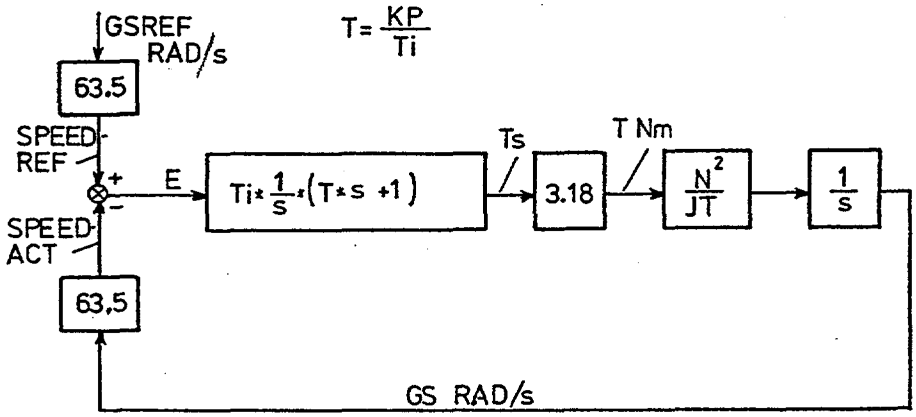


Figure 3.5:9 Speed control

From the figure the loop gain Ka and time constant T for actual values is obtained:

Ka= 3.3 T=0.95

This is a rather stiff control the upper frequency limit is about 3 Rad/s. This means that all disturbances caused by wind turbulence will interfere the drive train. Also part of the rotor speed dependent disturbances (2p gives 8 Rad/s etc.) will interfere to same extent as can be seen from the following diagram showing the drive train sensibility to aerodynamic disturbances with the control system included.

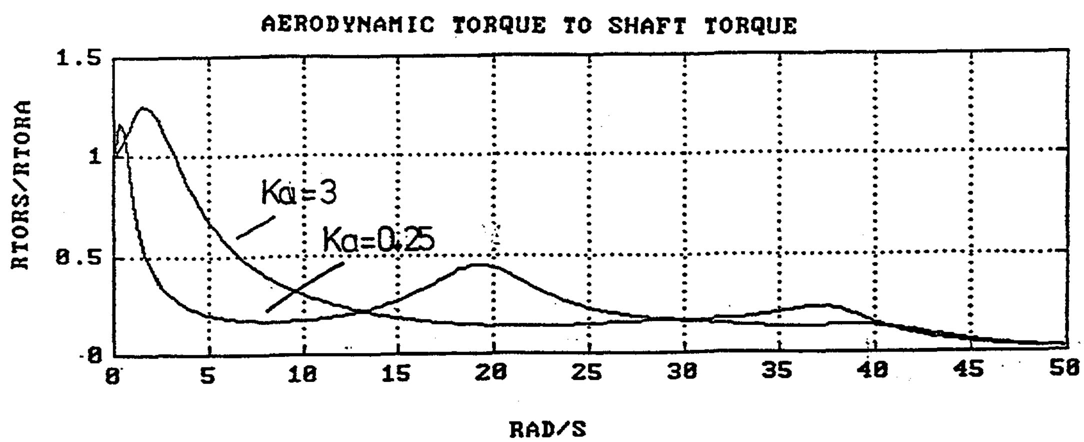


Figure 3.5:10 Drive-train sensitivity to aerodynamic disturbances

As can be seen from the diagram the drive train resonance is well damped for the actual gain. However, to get damping of the resonance more severe demands on the performance of the control must be established then is needed for the speed control. A lower gain Ka=0.25 gives smaller disturbances but the damping will be worse. If necessary this can be improved by means of a feed forward from generator speed to electrical torque.

3.5.2 Measurements and simulations

3.5.2.1 Simulations

Simulations with the value Ka=4 and a lower value Ka=0.25 have been performed for various cases. The following Figure shows an example with blade configuration B. Input is a rather turbulent wind speed. The simulations start in the stall region and drop during the first 20 seconds to the second region.

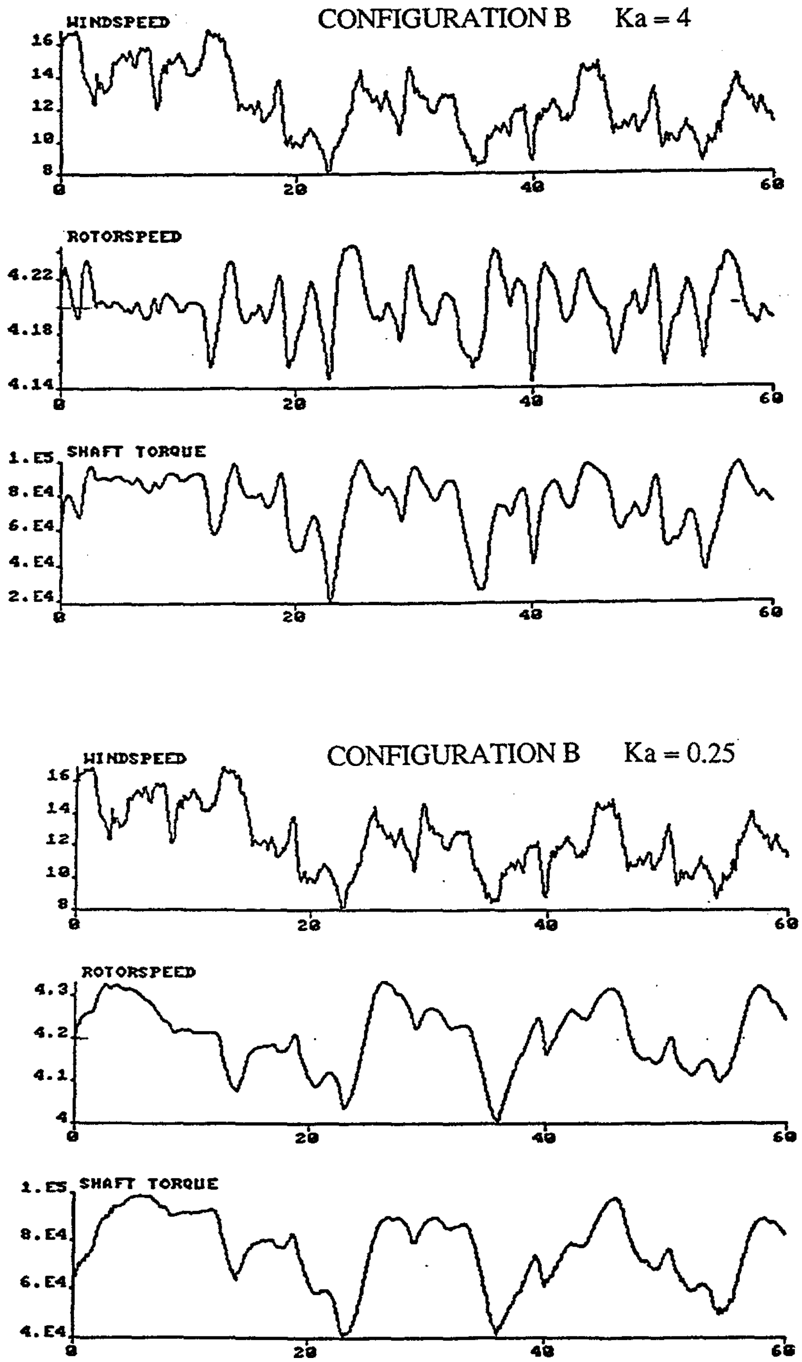


Figure 3.5:11 Simulations with Ka= 4 and 0.25

Of special interest is the shaft torque. It turns out that a looser control gives smoother shaft torque.

3.5.2.2 Measurements

A minor number of measurements has been performed.

Configuration B

- second mode of operation
- shut down

Configuration F

- stall mode
- second mode of operation
- optimal mode

The measurements are presented together with spectrum. Band pass filtering was used to determine disturbances of specific frequency. An example is shown in 3.5.2.3. The following conclusions were drawn from the evaluation of the measurements.

SPEED REGULATION

Very small variations in speed were noted, totally about 0.6 % of mean. This depends on the stiff control, but probably also on very low turbulence. As mentioned before, simulations with greater turbulence have been performed, see previous section.

DRIVE-TRAIN

No drive-train resonance has been found, probably depending on the large control gain which gives damping. However, at earlier identification tests, a resonance at about 18 Rad/s was found. Also it was difficult to distinguish between the drive-train resonance and 4p-disturbances.

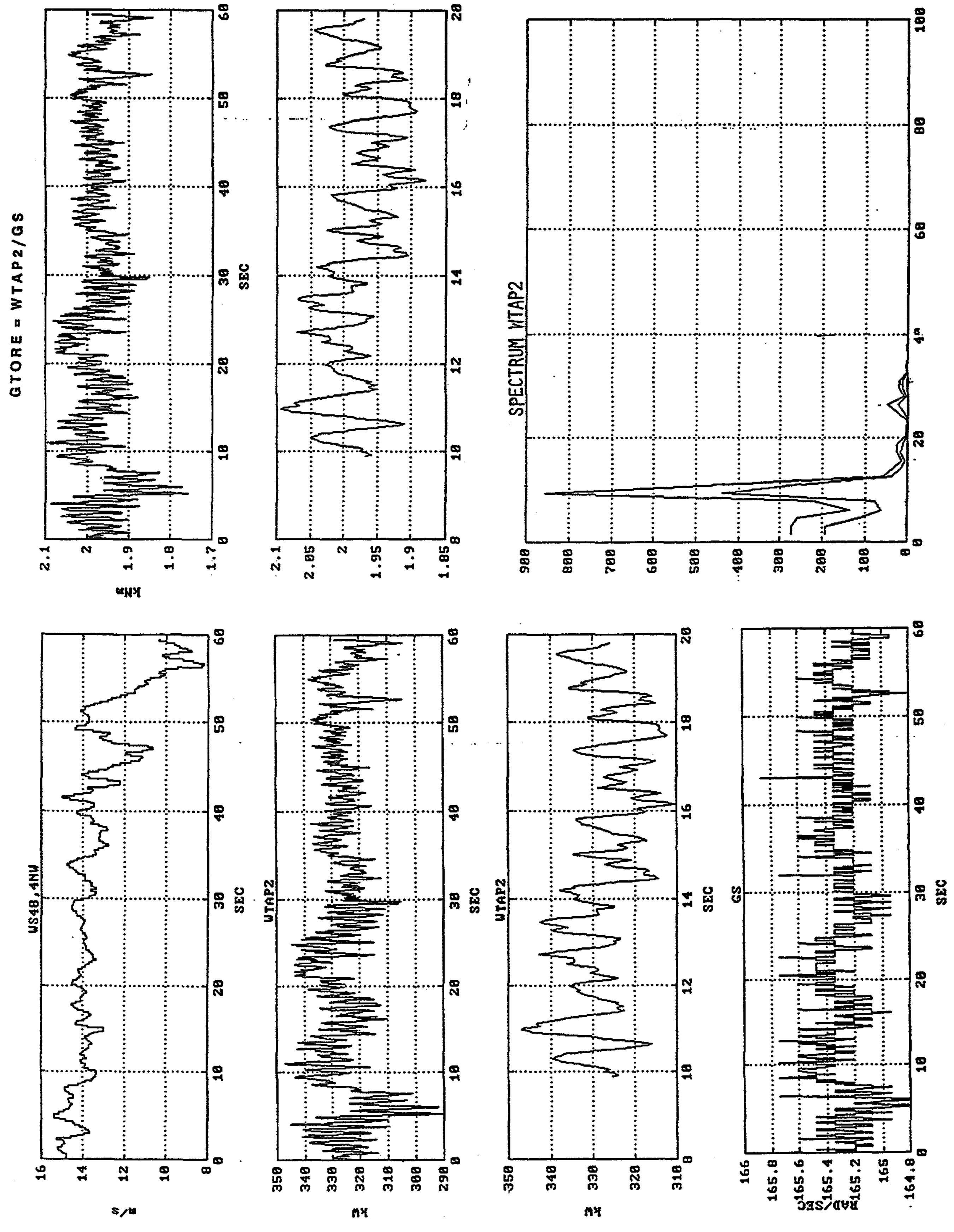
DISTURBANCES

Torque disturbances on the drive-train caused by turbulence are very small, probably dependent on low wind turbulence. However, rather heavy disturbances with a frequency corresponding to double rotor speed were found (2p-disturbances) and also smaller 4p- and 6p-disturbances was found.

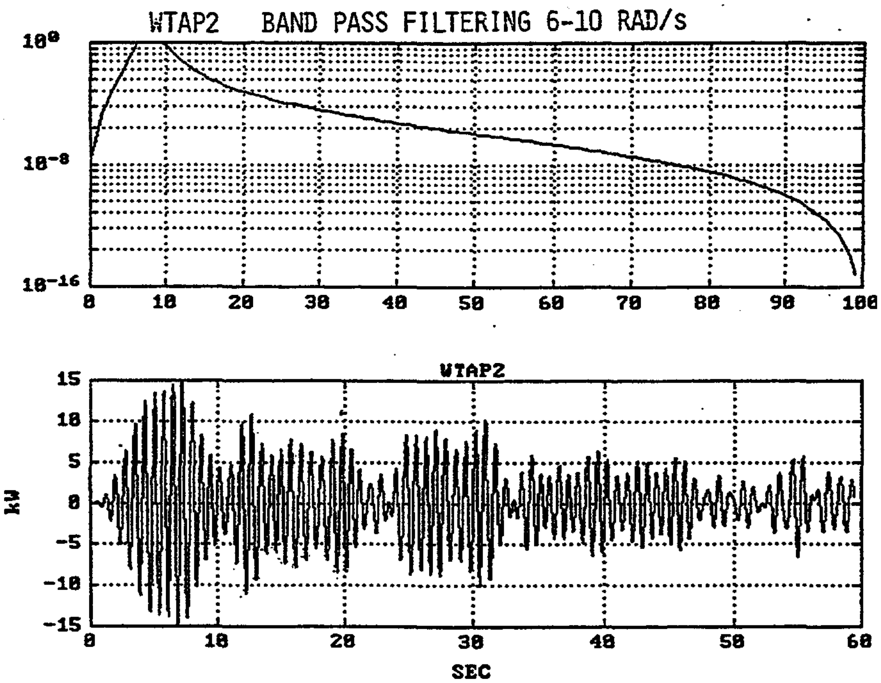
	2p	4p	6p	29 Rad/s
Config B				
second mode	150 Nm	(measurement difficulties)		
Config F				
stall mode	90 Nm	16 Nm	18 Nm	
second mode	90 Nm	15 Nm	24 Nm	55 Nm
optimal mode	90 Nm			

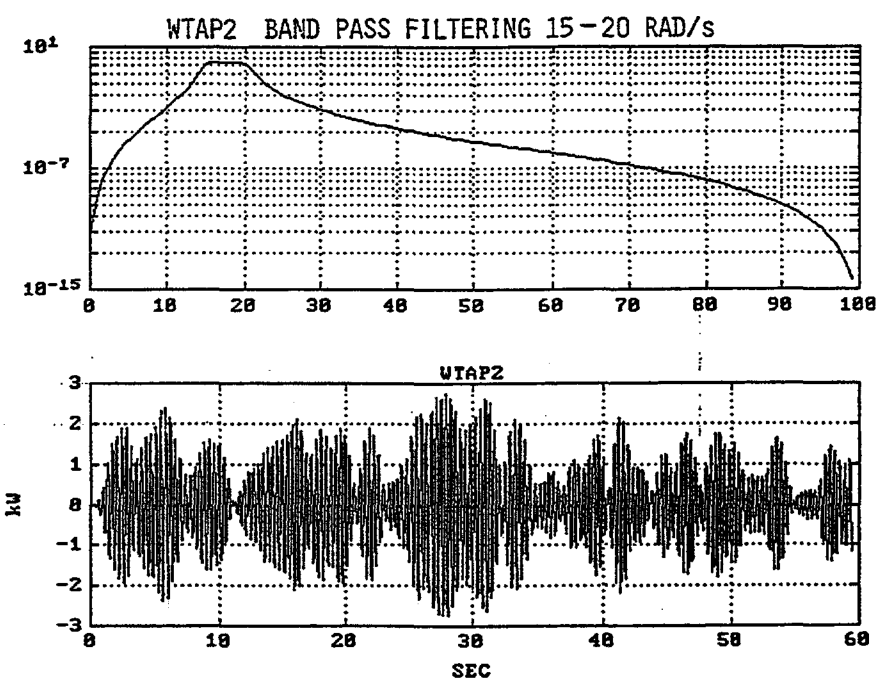
The Figures are the maximal amplitude of the sinusoidal disturbances. As can be seen from the Figure 3.5:10 these disturbances on the drive-train are only a minor part of the aerodynamic torque. The disturbance with frequency 29 Rad/s can be a 7p-disturbance, caused by lateral movements of the tower that has been observed in the structural investigation. Also yaw movements have been found at this frequency.

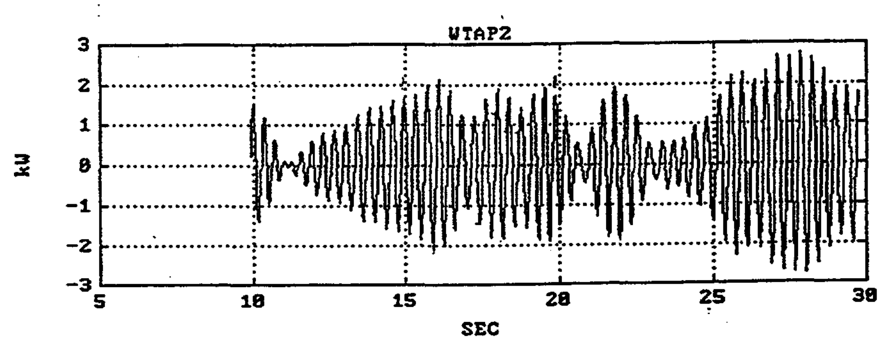
3.5.2.3 Example of measurements



Band pass filtering in order to determine speed dependent disturbances 2p, 4p.







3.6 DRIVE-TRAIN

3.6.1 Drive-system dynamics

The notation drive-system refers to the mechanical/electrical system that converts the kinetic energy in the incoming wind into electrical power, schematically described in Figure 3.6:1. Here are included the three main subsystems which represent the drive-train dynamics, the aerodynamics and the generator dynamics, described below.

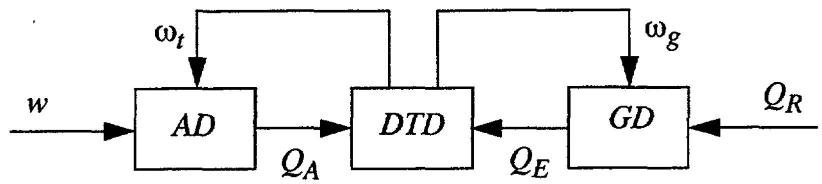


Figure 3.6:1. Schematic drive-system model, including: DTD=drive-train dynamics, AD=turbine aerodyn., GD=generator dyn.,w=wind-speed, QA=aerodyn. torque, QE=generator torque, QR=generator torque reference, ω_t, ω_g=turbine, generator rotational speed

Drive-train

Throughout the modelling, the nomenclature "turbine inertia" and "generator inertia" will be used. However, the actual partitioning (lumping) of the total drive-train inertia (blades, hub, drive shaft, gearbox and generator) is not known, since we have no à-priori knowledge of where the fundamental resonance originates. (It is thus not presupposed that the fundamental mode appears in the main shaft connecting the turbine to the generator.)

The default model, Figure 3.6:2, includes two masses, yielding one single resonant mode. The reason to use this model as default, is that it is simple, yet it incorporates the dominating first drive-train mode

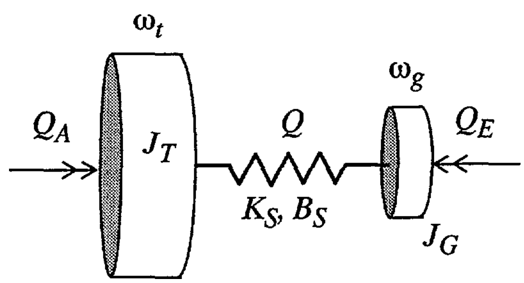


Figure 3.6:2 Default physical model of drive-train. JT, JG=turbine and generator inertias, K_S, B_S=shaft compliance and damping.

The corresponding frequency response from Q_E (control signal) to ω_g (measured output) is depicted in Figure 3.6:3. In the plot, the following à-priori (construction data) parameter values[1] of the inertias and shaft stiffness for the NWP turbine have been used:

J_T=180,000 kgm^2
J_G=23,000 kgm^2
K_S=1,500,000 kgm^2/s^2

The fundamental frequency, using these values, is thus 27 rad/s = $\left(\sqrt{K_s 1/(J_T + 1/J_G)}\right)$

[1]The used values are the original values supplied by the contractor. These have gradually been subject to corrections, however, not accounted for here.

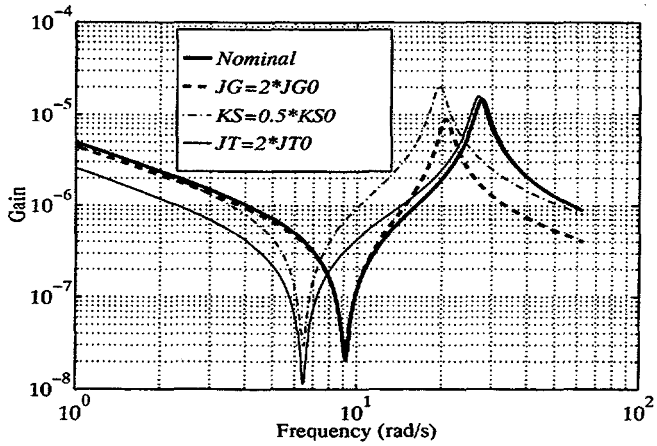


Figure 3.6:3 Frequency response from Q_E to ω_g for two-mass drive-train model, for à priori parameter values of NWP (bold line). Also shown: curves corresponding to individual variations of the parameter values. ("JTO" signifies the nominal value of J_T, etc.)

If one requires a model that is relevant in a larger frequency range, a higher model complexity is needed.

Generally, the control action can be chosen relatively fast in the low wind, or partial load, region since here the load dc level and variations are lower and therefore less damaging for the components and the structure. It should be obvious that the higher the demands are on power maximisation, the more important it is to use a detailed model and to optimise the controller w.r.t.. the model. The main restriction in the obtainable controller band width is, however, the quality of the wind speed measurements (estimates).

3.6.2 Identification

This chapter presents the identification results from three experiments made on NWP400, during the period of June 1993 to November 1994. The experimental set-up, Figure 3.6:4, was in closed loop for security reasons. The excitation was improved by adding a stochastic signal to the controller output, as will be described below. In the measurements it is noteworthy that the measured input was the generator-torque reference signal which is fed into the vector control unit of the frequency converter. The reason for using this as input and not the actual generator torque is that the latter signal is available only as a low-pass filtered (averaged) signal. However, it is known à-priori that the fundamental dynamics of the frequency converter are considerably faster than the fundamental drive-train dynamics and can therefore be neglected in the modelling. This means that in the experiments, the torque references are assumed identical to the real torque (Q_E), according to what was said in Chapter 3.6.1. The sensor was assumed ideal in the frequency range of interest.

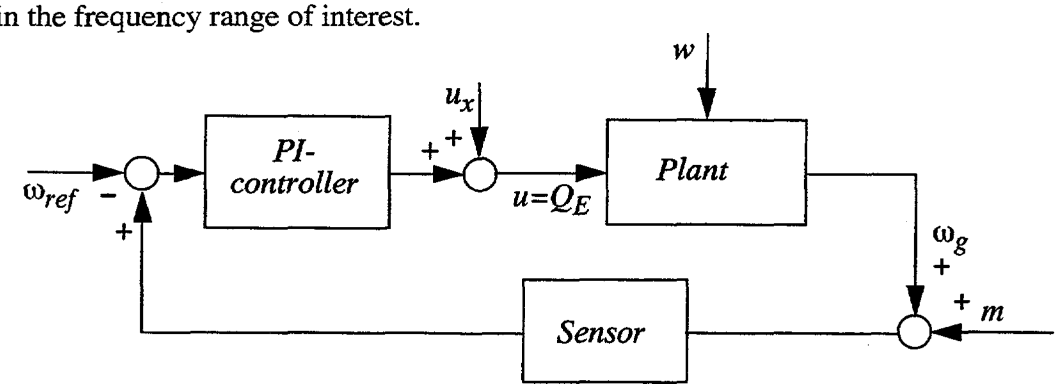


Figure 3.6:4 Experiment layout, block diagram ω_{ref}=speed set point, Q_E=electrical torque (reference) u_X=extra input, w=wind-speed, m=measurement noise.

An outer reference speed loop which is supposed to update the set point according to low-frequent changes in the mean wind speed was not used during the experiments; instead the set-point was given a constant value.

3.6.2.1 Data collection

The collected data from the three occasions (hence forth referred to as Data1, Data2 and Data3) were taken at different weather conditions. At the first occasion (June 1993) the wind was low, averaging less than 5 m/s, and therefore providing good experimental conditions (due to a high signal-to-noise ratio). As a contrast, at both the second and third occasion (September and November 1994) the wind was strong, averaging 20 m/s.

Minor modifications were made on the drive-train between the first and second occasion. These modifications concerned the teetered hub (spring constant and maximum angle) and were unlikely to affect the dynamics in the plane of rotation.

During all the sessions, the plant was run in closed loop provided by a PI-controller, which produces the generator-torque reference signal based on measurements of the generator speed. In order to improve the excitation a PRBS signal, u_X, was added to the controller output. The characteristics of this additional PRBS input were determined from physical knowledge and a step response which showed a dominating closed loop resonance at 3 Hz (Figure 3.6:5). The amplitudes of the PRBS were 2.5, 5, and 8% of nominal torque respectively at the three occasions. The minimum time between subsequent PRBS switches was 240 millisecs for Data1 and Data2, decreased to 96 millisecs for Data3 to provide excitation of higher frequencies, possibly revealing a second resonant mode. The latter, however, proved not feasible due to a too low bandwidth of the velocity sensor.

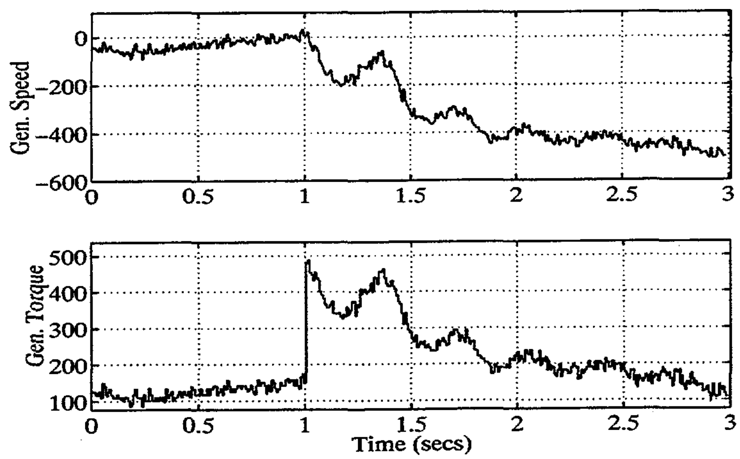


Figure 3.6:5. Closed-loop step-response. Note that the step response has not yet reached stationarity at the end of the plot.

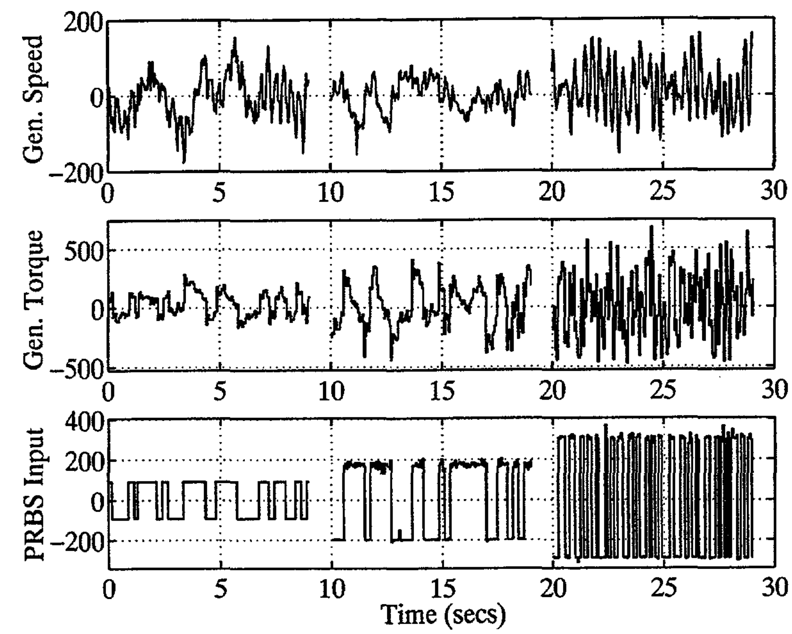


Figure 3.6:6. Sequences of the three data series in the same diagram (switches after 0 and 20 seconds, respectively). From left to right; Data1, Data2 and Data 3. The PRBS input is measured for Data 2 and 3 while reproduced for Data 1, assumed ideally square.

The data series of Figure 3.6:6 show some differences that can be explained by the different levels of wind disturbance and the above mentioned differences in the added input u_X, especially for the more high-frequent Data3. The corresponding power spectra Figure 3.6:7 provide some information about the signals. Since the sampling frequency was 20 Hz the normalised frequency range covers 0 to 10 Hz (the Nyquist frequency). The inputs from Data1 and Data2 clearly show the PRBS-spectrum influence with dips at the clock frequency (here 0.24^{-1}=4.2 Hz) and multiples thereof, which are superimposed on the spectrum of the closed loop signal. For the Data3 input there is no dip at 4 Hz since the clock frequency was here 0.096^{-1}=10.4 Hz, just outside the plotted range. The high overall level of the Data3 input spectrum, except for the lowest frequencies, is explained by the high amplitude of both u_X and the closed loop signal, and the increased bandwidth of u_X.

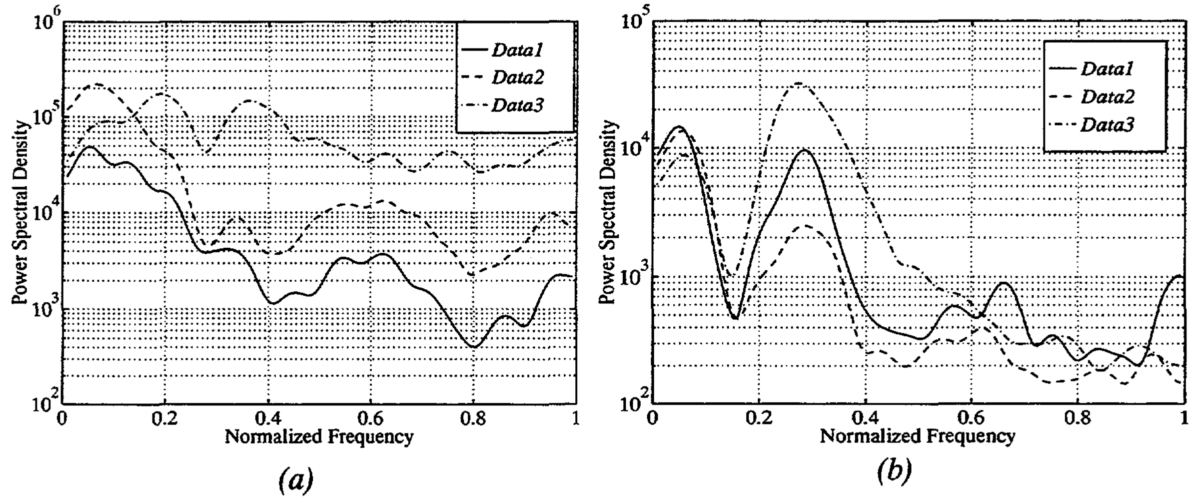


Figure 3.6:7 (a) Input Q_E and (b) output ω_g power spectra for the data sets.
The normalised frequency 1 corresponds to the Nyquist frequency (10 Hz).

In the output spectra there is a clear, local maximum around 3 Hz, which corresponds to the fundamental closed loop resonance. The most low-frequent peak of the output spectrum just below 1 Hz corresponds to 2p, i.e. twice the rotational frequency. This is to be expected for a two-bladed machine, due to the disturbance effects when a blade passes the tower.

3.6.2.2 Spectral Analysis

The estimation method first used on measured data is often spectral analysis since it demands no prior assumptions being made on the model structure or order. In this case, working in closed loop, the standard method is not applicable since it does not require correlation between the input and the disturbances. Applying an indirect method using the independent extra input, the following holds:

$$\omega_g(k) = G(q)Q_E(k) \Rightarrow \Phi_{\omega_g u_x}(\omega) = G(i\omega)\Phi_{Q_E u_x}(\omega) + \Phi_{nu_x}(\omega) \tag{3.6.1}$$

where the last term is zero, why the following estimate can be formed:

$$\hat{G}(i\omega) = \frac{\hat{\Phi}_{\omega_g u_x}(\omega)}{\hat{\Phi}_{Q_E u_x}(\omega)} \tag{3.6.2}$$

The main freedom in shaping the frequency response estimate is in the choosing of lag-window characteristics, which control the correlation between estimated values at adjacent frequency-points. The choice of window size is based on a more or less objective decision of when the weighting has produced a suitable trade-off between bias and variance in the estimate.

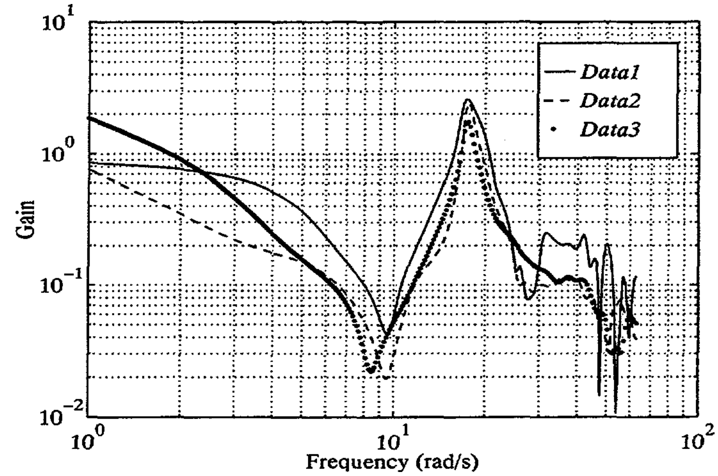


Figure 3.6:8 Spectral nalysis estimates from the three data sets.

For the data series, the resulting gains of the three spectral estimates of $G(i\omega)$, Figure 3.6:8 all include the expected shape, corresponding to a two-mass, under-damped system. There is good

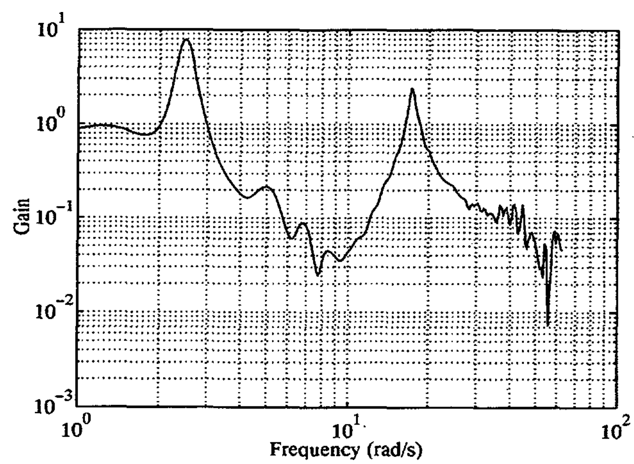


Figure 3.6:9 Spectral-analysis estimates from Data1, wider lag window than in Figure 3.6:8.

mutual correspondence in the estimated fundamental resonance frequency (ω_2 which appears close to 17 rad/s = 2.7 Hz, i.e. clearly below the à-priori value of 27 rad/s, cf. Figure 3.6:3. Also the anti-resonance is clearly visible for each estimated curve, however, this frequency ω_1 varies more between the estimates than the resonance frequency. For lower frequencies there is an even larger discrepancy. This can be explained by the different operating conditions, which affect the aerodynamics and thereby the low-frequency characteristics. Furthermore, the turbine velocity for Data2 and Data3 was increased compared to Data1, pushing low multiples of the rotational frequency close to the frequency range of the drive-train resonance. This appears more clearly when the lag-window is widened (Figure 3.6:9), allowing narrow spectral peaks to emerge. The peak at 2.5 rad/s (followed by peaks at multiples of the frequency) corresponds to 1p, i.e. the rotational frequency 25 rpm. (For higher frequencies, above ω_2, the estimates are subject to sensor restrictions and disturbances and are therefore unreliable).

3.6.2.3 Agreement with physical model structure

The anticipated structure of a slow, real pole followed by an antiresonance and a resonance is verified by parametric black box model identification. As for the spectral analysis models, the estimate of the resonance frequency, ω_2, are more in agreement than those of the anti-resonance frequency, ω_1. The relative damping differs somewhat but is for all models very low, not exceeding 0.06–0.07. This makes it, in effect, negligible as compared to the damping provided by active feedback, and therefore of low relevance. Also, there is a clear difference between the estimated values of the slow, real pole. Recall, that this pole corresponds to the linearized aerodynamics, which are dependent on the operating point and therefore vary between (and also during) the collected data sets. Moreover, the pole is in a frequency band that is corrupted by disturbances (multiples of the rotational frequency) which makes the estimation difficult.

The identification results indicate that the simple physical drive-train model of Chapter 3.6.1 gives good agreement in the low frequency range that has been treated. It is clear, that the system does have an antiresonance around 9 rad/s followed by a lightly damped resonant mode at 17 rad/s, corresponding to the interaction of two inertias with a compliant interconnection. The results of the black-box modelling, as well as the spectral analysis models, are in good agreement regarding the fundamental resonance frequency. Notable is that the à-priori-based value of this frequency (27 rad/s) largely deviates.

The main purpose of this chapter has been to extract values of the mechanical quantities, i.e. the two inertias and the shaft compliance, in the underlying physical model. The estimated values of these parameters were in fairly good agreement between the identified models, but significantly different from the à-priori values. The large difference in the inertia ratio, J_T/J_G, indicates that the turbine should not be modelled as a rigid body, but as a two-mass system.

3.7 WIND MEASUREMENTS

3.7.1 Introduction

With a growing interest for wind energy, the demand for sites suitable for wind turbines will increase. A consequence of this is that turbines can not only be located in the most favourable areas, but also locations with more complex terrain have to be considered. An example of this is coastal areas with archipelagos. From a meteorological point of view, this means that the requirements on measurements and models used for siting will increase, not only in order to get better predictions of the wind potential, but also to get more reliable wind data to be used as input to wind turbine load calculations, i.e. turbulence characteristics, vertical and horizontal wind gradients.

3.7.2 Site and measurements

A map of the measurement site located at Lyse Wind Power Station in the northern part of the Swedish west coast, is shown in 3.7:1. This is a rather heterogeneous area, with an archipelago of rocky islands reaching typically 30 m to 50 m above sea level. Also the nearby mainland is non-homogeneous with many rocky parts with peaks and plateaus up to about 50 m in height. The vegetation is sparse over large areas, and bare rocks with only low herbs, mosses and lichen are common. But on the mainland there are some scattered groves and meadows, and occasionally some agricultural land.

The meteorological tower is 66 m high with a square cross section, decreasing in width with height. The tower is 4.36 m wide at the bottom, 3.44 m at the height 12 m, 2.52 m at 24 m, 1.60 m at 36 m, and 0.90 m above the 48 m height. It has been instrumented with combined cup/wind vane anemometers, (Bergström and Lundin, 1993), at 7 heights, giving information on mean wind conditions and turbulence characteristics of both longitudinal and lateral wind components. To be able to get measurements which are undisturbed from the tower itself for all directions, the upper five levels are equipped with two anemometers at each level, pointing in opposite directions, one towards northwest (308°) and the other towards southeast (128°). In 3.7:2 details of the instrument mounting are shown. The anemometers are sampled with the frequency 1 Hz, and comparisons with a hot-film instrument, (Smedman et.al, 1991), show good agreement both as regards spectra and turbulence statistics.

Before they were mounted on the tower, the anemometers were calibrated in a wind tunnel at The Royal Institute of Technology in Stockholm (KTH). The tunnel has an octagonal cross section with the height 1.2 m and the width 1.5 m. During calibration the anemometers were mounted on a short boom pointing upstream, and placed in the centre of the tunnel. Calibration was made at a number of speeds from 3 to 30 m/s, and a Pitot tube was used to check the tunnel speed at the measurement point. A second order polynomial was adapted to the calibration data and used in the evaluation. Individual calibrations were used for the 12 anemometers, although a comparison revealed that the anemometers themselves gave almost identical calibration curves when calibrated with one and the same cup. The cups were somewhat more individual, differing at most about 1%. Using individual calibrations reduce the expected calibration error to a few tenths of a percent.

To get information about the thermal stability of the atmosphere, temperature is measured at five heights, using ventilated and radiation shielded Pt-500 thermometers. At 2 m height the air pressure and relative humidity are measured. Details on the instrumentation and measurement heights are given in Table 3.7:1.

Data is sampled on a PC (IBM compatible) with a time resolution of 1 s. It is temporarily stored on a hard disc for 3 days, and then a backup is made on a Wangtek 1 Gb steamer tape station. This measurement system is only used for the meteorological data, and is separate from the system described in Section 1.4. It has auto start, which means that when the power returns after a period of disconnection, the measurements will start automatically again. An on-line processing of data is also made, and 10 min averages calculated, presented on the monitor, and stored together with the 1 Hz data.

z (m)	Anemometer on boom towards NW	Anemometer on boom towards SE	Temperature	Height (m)
2.8			X	
10.8	X		X	
24	X		X	
32	X	X		12.1
40.4	X	X	X	12.5
49.1	X	X		7.1
57.8	X	X		7.1
65.2	X	X	X	7.1

Table 3.7:1 Tower instrumentation giving: z=height above ground, H=horizontal distance between anemometers on levels with two instruments.

Looking at the site in somewhat more detail, we see from Figure 3.7:1 that the measuring tower together with the two turbines are located on a small island, Basteviksholmen. Thus there are water areas upstream from the tower open not only for winds from the western sector, from the sea, but also for easterly winds, from the mainland.

In the western sector there are several islands at distances between 500 m and 1500 m from the tower. The free over water fetch for winds around west is of the order 500 m, at which distance we find the 40 m high island Bläckhall, about 500 m wide in the east-west direction. In the south-southwest direction, the distance to the nearest island, the 30 m high Stora Kornö, is about 1400 m. The distance to the mainland is about 500 m for easterly winds. The terrain here is very steep, with cliffs rising almost immediately to 20-30 m heights. Further inland some peaks reach 50 m above sea level.

By analysing and comparing the tower data from different wind direction sectors, it is consequently possible to study in somewhat more detail and to quantify the influence from quite different upstream conditions in this type of heterogeneous coastal area. Thus, e.g. mean wind profiles, turbulence intensities, and spectra may be compared with results from 'ideal' sites with homogeneous surface conditions, or to results from internal boundary layer growth studies. Further it will be possible to test models of different complexity against the observations.

3.7.3 Mean wind conditions - climatological wind distribution

Data from the period June 1993 to March 1995 have been used throughout this report. To study the mean wind conditions 10 min consequtive averages have been determined. Data is available from 99.5% of the period (95871 observations).

To be able to estimate the climatological wind conditions at Lyse wind power station, data from the climatological station at Måseskär about 25 km southwest of Lyse have been used. As the cup anemometers at the 58 m level at Lyse were all right during the whole period studied, this height was used for the comparison with Måseskär. Observed monthly averages of the mean wind speed at Måseskär and at Lyse during the period June 1993 to March 1995 are given in Table 3.7:2.

	Måseskär, height 25 m		Lyse, height 58 m	
	9306–9503	climat.mean	9306–9503	climat.mean
Jan	9.57	8.05	7.94	6.75
Feb	19.06	7.23	8.31	6.44
Mar	10.25	7.33	9.15	6.49
Apr	7.12	6.86	7.03	6.85
May	5.81	6.43	5.11	5.64
Jun	8.01	6.68	7.45	6.28
Jul	6.43	6.69	5.78	5.96
Aug	7.4	6.59	6.24	5.47
Sep	8.05	8.25	7.14	7.43
Oct	7.52	8.38	6.87	7.53
Nov	7.93	9.07	6.73	7.82
Dec	9.99	8.88	8.71	7.66
year	8.24	7.54	7.3	6.63

Table 3.7: 2 Observed monthly averages of mean wind speed at Lyse and at Måseskär during the period June 1993 to March 1995, together with climatological mean wind speed at Måseskär 1961-1980 and the estimated climatological mean wind speed at Lyse as determined from Eq. (1).

Also given in this table are the corresponding climatological averages. Due to the heterogeneous terrain at Lyse, wind direction was considered when estimating the climatological mean wind speed at Lyse. This was accomplished by first dividing the data into 8 wind direction classes - NE, E, ... NW and N. Comparisons between simultaneous observations at Lyse and at Måseskär were then made for each wind direction sector, and monthly correction factors could be determined for each of these sectors. Data from the period 1961-1980 have been used to get the wind climatology at Måseskär.

As we can see from the table, data from the period 9306-9503 may not directly be taken to represent the wind climatology. At Måseskär the annual mean wind speed determined from this 22 month period is 9% higher than the climatological value during the 20 year period 1961-1980. Thus wind measurements from a period as short as two years may, as expected, give quite an erroneous wind climatology if not corrected by comparing them (the measurements) with data from a nearby climatological station. At the 58 m level at Lyse, the measured mean wind speed is 10% higher than the climatological mean wind speed, estimated taking into account the actual wind direction.

The frequency distribution of 10 min mean wind speed at Lyse, 58 m height, during the period 9306-9503 is shown in Figure 3.7:3. This distribution is commonly approximated by the Weibull distribution, whos cumulative distribution is given by

$$F(U) = e^{-(U/A)^c} = 2^{-(U/U_m)^c} \tag{1}$$

where U = wind speed (m/s)
A = scale factor (m/s)
c = form factor
U_m = median wind speed (m/s)
F = cumulative frequency [0;1].

Thus the Weibull distribution is described by the two parameters A and c. Adapting the observed distribution at the 58 m height to the Weibull distribution gives A=8.0 m/s and c=1.93. As we have seen above, the mean wind speed during the measuring period was higher than the climatological value. Correcting the scale factor for this will give the climatological scale factor 7.4 m/s.

The wind direction distribution observed at Lyse during the period 9306-9503 is shown in Figure 3.7:4. Two distinct peaks may be observed, one more dominant for winds around southwest, and one for winds from north-northeast. The least frequent wind directions were those around north.

The same general pattern show up in the wind direction distribution at Måseskär, given in Figure 3.7:5 (the bar width is here 45° because the climatological values from Måseskär are only available with this resolution), although the observations during the period 9306-9503 also indicate a maximum around south. This third maximum is not present in the climatological wind direction distribution, also given in Figure 3.7:5. The wind direction climatology at Lyse and at Måseskär may also differ somewhat due to the longer distance from the coast to Måseskär, whereby the influence from the local topography and from the sea breeze may alter the wind direction to some extent.

3.7.4 Mean wind profiles

Due to the fact that the anemometer cups during some periods were defect at one or several measuring heights, data had to be checked for this before determining mean wind profiles. Only periods when data from all 7 heights were available have been used here. This reduces the number of 10 min periods from 95871 to 43089, i.e. to about 45% of the time. The majority of the missing data is from parts of the period April to September 1994.

Figure 3.7:6 shows the observed total mean wind profile when data from all wind directions have been used (x), together with a climatologically corrected wind profile (o). The climatological mean profile was determined by using the climatological value which we got by comparing the 58 m level measurements 9306-9503 at Lyse with simultaneous data from the climatological station at Måseskär, cf. the previous Section, assuming the same ratio between

3.7.5 Summary and conclusions

The mean wind and turbulence characteristics at Lyse during the period from June 1993 to March 1995 have been studied. One conclusion of the analysis is that in spite of the rather heterogeneous surroundings with rocky terrain at various distances in all directions, the turbulence levels are by no means extremely high. Neither is the mean wind gradient extreme. Instead, as a mean, the wind profile shows a much smaller vertical gradient below 30 m than might have been expected even over the open sea, while above 40 m the wind gradient is somewhat larger than over the sea. As a result of this, the mean wind speed at Lyse varies approximately linearly with height, insted of the logarithmic height variation which is expected over homogeneous terrain.

The reason for this is that, except for northerly and southerly winds, the tower site is surrounded by water areas, typically 500-1500 m wide, and further away rocky islands to the west or the equally rocky mainland to the east. Thus a wind turbine at the location of the tower, on a very tiny island, will work in a mean wind gradient which is smaller than if the island had been larger or if it had been located on the mainland at some distance from the coast. The same reasoning is valid for the turbulence intensity, which due to the surrounding water areas will increase much less with decreasing height than in a homogeneous rocky terrain.

Comparisons with theoretical relations for both mean wind profiles and profiles of turbulence intensity show that the conditions above 40 m with wind directions from the land sector are about the same as the conditions over homogeneous terrain with a roughness length of the order 0.1-0.2 m. This roughly corresponds to the conditions over agricultural areas with groves, hedges, scattered buildings and villages. With winds from the rocky islands in the western sector, the wind characteristics above 40 m are about the same as in homogeneous areas with the roughness length 0.01-0.02 m. This corresponds to conditions over fairly level grass plains or farmland with only very few buildings and trees, seldom found in Sweden.

The largest turbulence levels are of course observed in the wake from the two wind turbines, one to the north and one to the south of the tower. But also winds from a narrow sector around 220° show unexpectedly high turbulence levels and large mean wind gradients above 40 m. The conditions in this sector is about the same as with winds from land as regards the turbulence levels, while the mean wind gradient is even larger, corresponding to a roughness length of 0.5m. The cause for these rather extreme conditions in this narrow sector seems to be a combined effect of the upwind trajectory passing over the southeastern corner of the island Bläckhall, and further away passage over a main part of the larger island Stora Kornö.

An analysis were made of the 1 s vertical wind gradient values, divided into an asymmetric and a symmetric part, and evaluated at the height 49 m using data from the height interval 32 m to 65 m. It revealed that the standard deviation of these turbulent gradients as a mean could be related to the standard deviation of the longitudinal wind component, but that variations in these relations were found depending on the upstream conditions and also on the thermal stability. The distribution of the 1 s asymetric gradients showed that the difference in 1 s wind speed between the 65 m and the 32 m levels have an extreme range between about -9 m/s and 16 m/s.

Spectra were determined at the 32 m and 65 m heights, and show rather good agreement with semiempirical relations from homogeneous terrain. The coherence between these two levels was on the other hand smaller than expected from data over homogeneous areas. This is probably a consequence of the internal boundary layers which for most wind directions will have the height 30-50 m at the tower. Due to this the correlation between the turbulence in the upper and lower parts of the tower might be expected to be smaller as compared to homogeneous conditions.

A climatological wind profile was estimated using simultaneous wind observations at Lyse and at the climate station at Måseskär, 25 km to the southwest of Lyse, during the period June 1993 to March 1995. Weighting functions were determined for each month and for 8 wind direction sectors, also allowing the climate wind data from Måseskär 1961-1980 to be used to estimate the corresponding wind climate at Lyse. It was found that the reduction in mean wind speed at Lyse compared to the conditions at Måseskär is quite large. At Måseskär the mean wind speed 25 m above sea level is 7.5 m/s, while at the height 24 m at Lyse the mean wind speed is 5.9 m/s, a reduction of about 21%. At the 65 m level the mean wind speed at Lyse has increased to 6.8 m/s, still about 9% below the 25 m value at Måseskär.

In the future it is of course possible to further analyse the meteorological data from Lyse. More detailed studies of the conditions in specific sectors may be of interest, e.g. the sector 218-223° in which the turbulenc levels are higher than expected and the wind gradient larger. Also other sectors than those analysed here may give additional information regarding the wind conditons at Lyse. A more thorough analysis of the influence from the thermal stability and its eventual importance to wind energy applications would be valuable. The 1 Hz data is also a valuable database to be used in the search for and investigation of extreme wind situations. It would be very interesting to locate the 10 or 20 most extreme cases in the data, and compared with the extreme conditons used for the wind turbine designing.

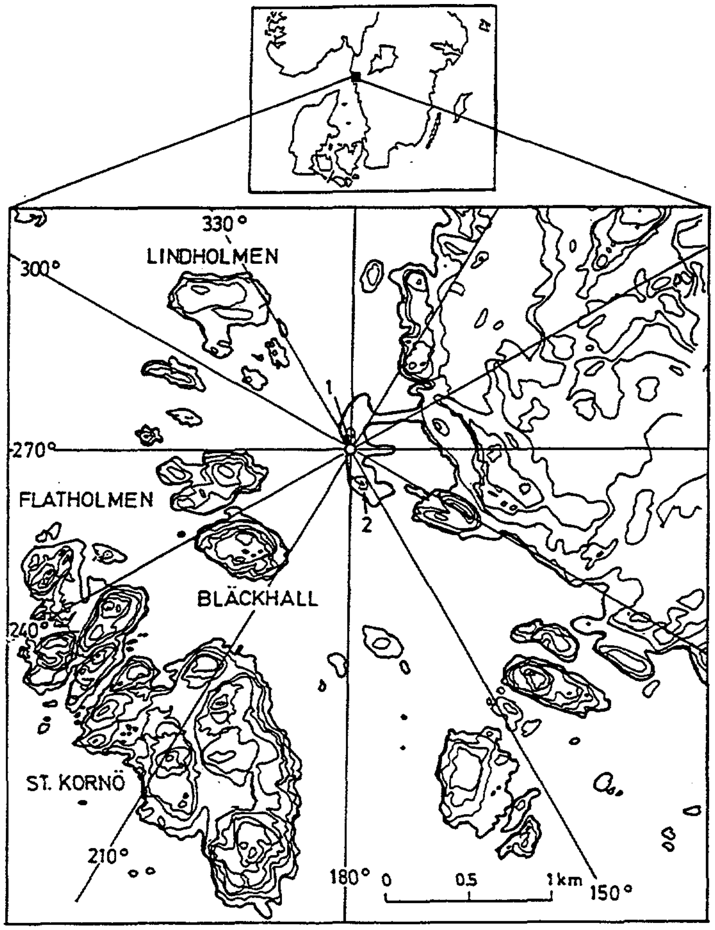


Figure 3.7:1. Map of the measurement area showing tower (o), NWP400 turbine (1), and Bonus turbine (2).

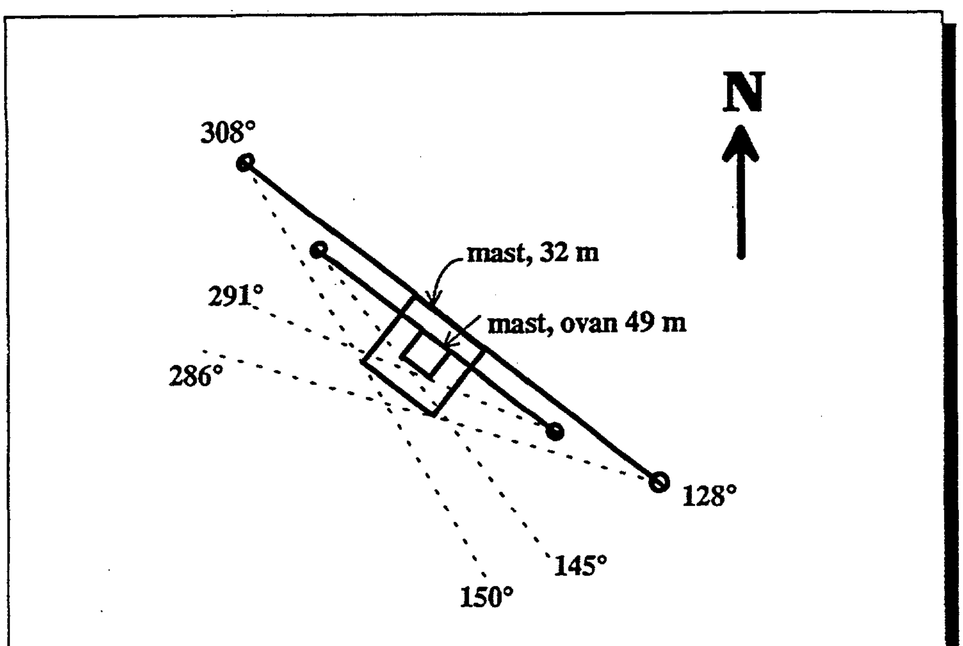


Figure 3.7:2. Scetch of the meteorological tower seen from above. The tower and booms at two heights (32 m and 49 m) are shown. The angles give the sectors from which the wind is passing through the tower upstream the anemometers. The anemometers on the SE-side of the tower are thus behind the tower for winds from the sector 291-308° at 49 m, and from the sector 286-308° at the 32 m level.

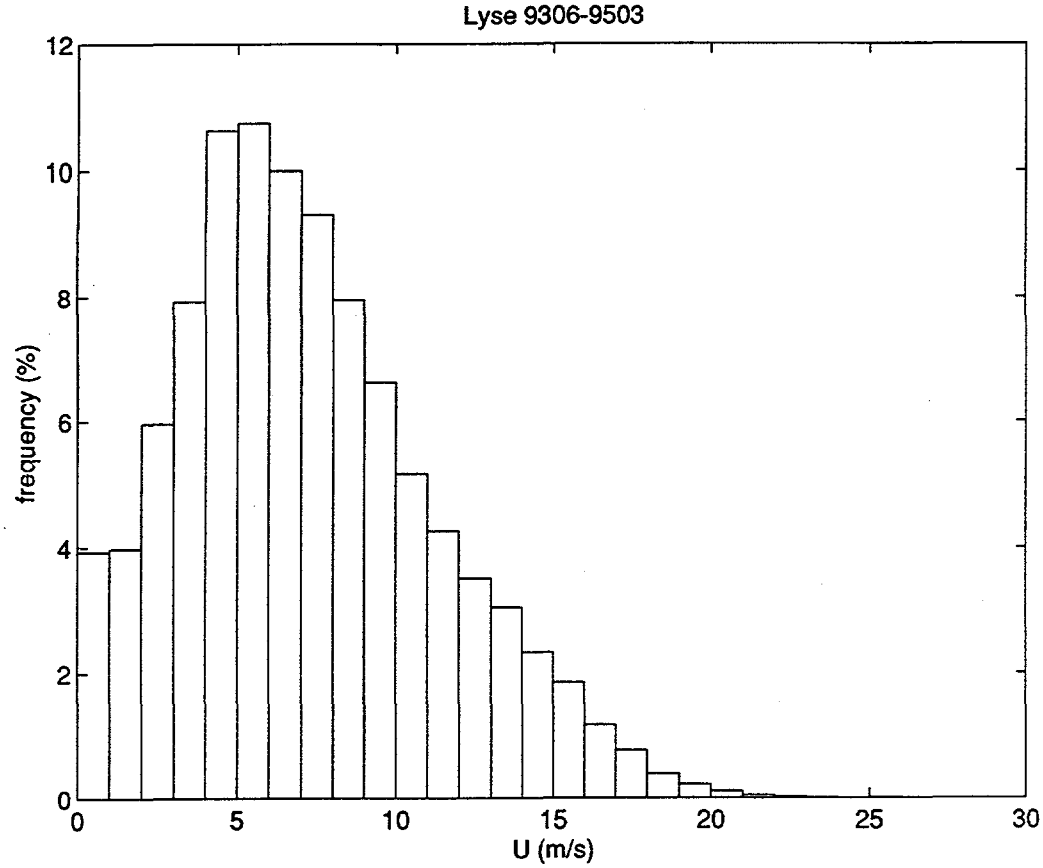


Figure 3.7:3. Observed frequency distribution of the 10 min mean wind speed at Lyse, 58 m height, during the period 9306-9503.

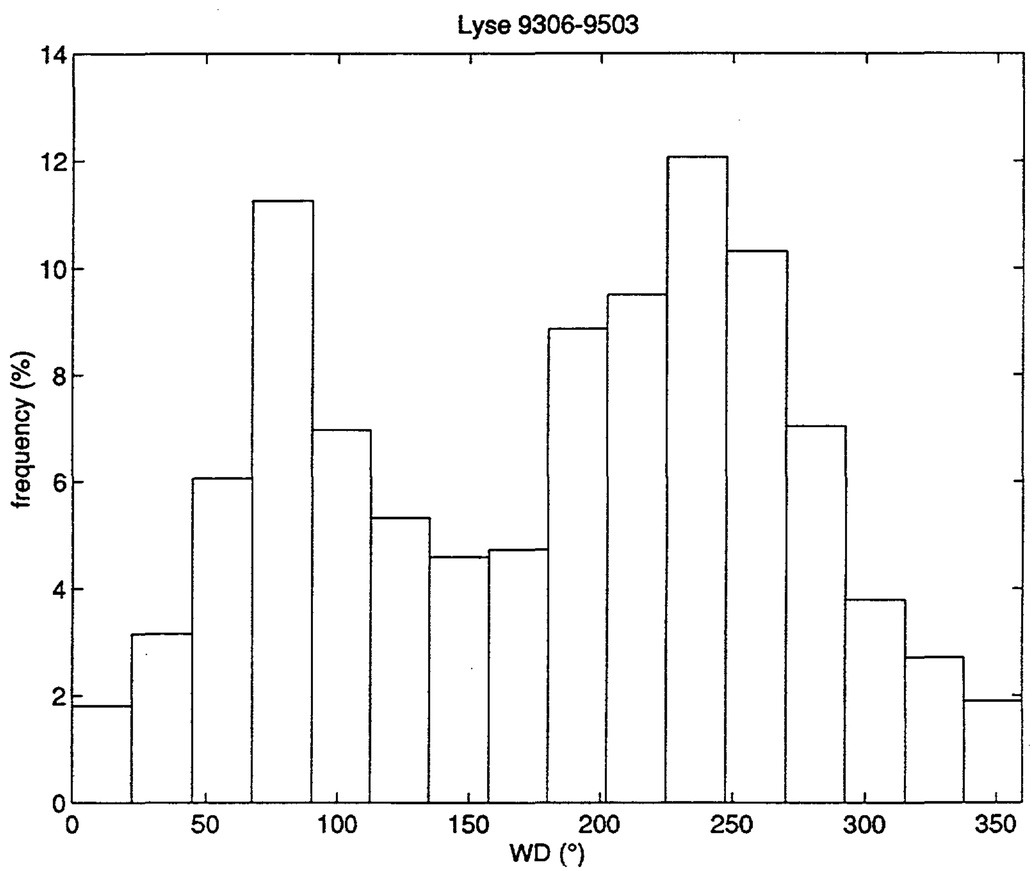


Figure 3.7:4. Observed wind direction distribution at Lyse during the period 9306-9503.

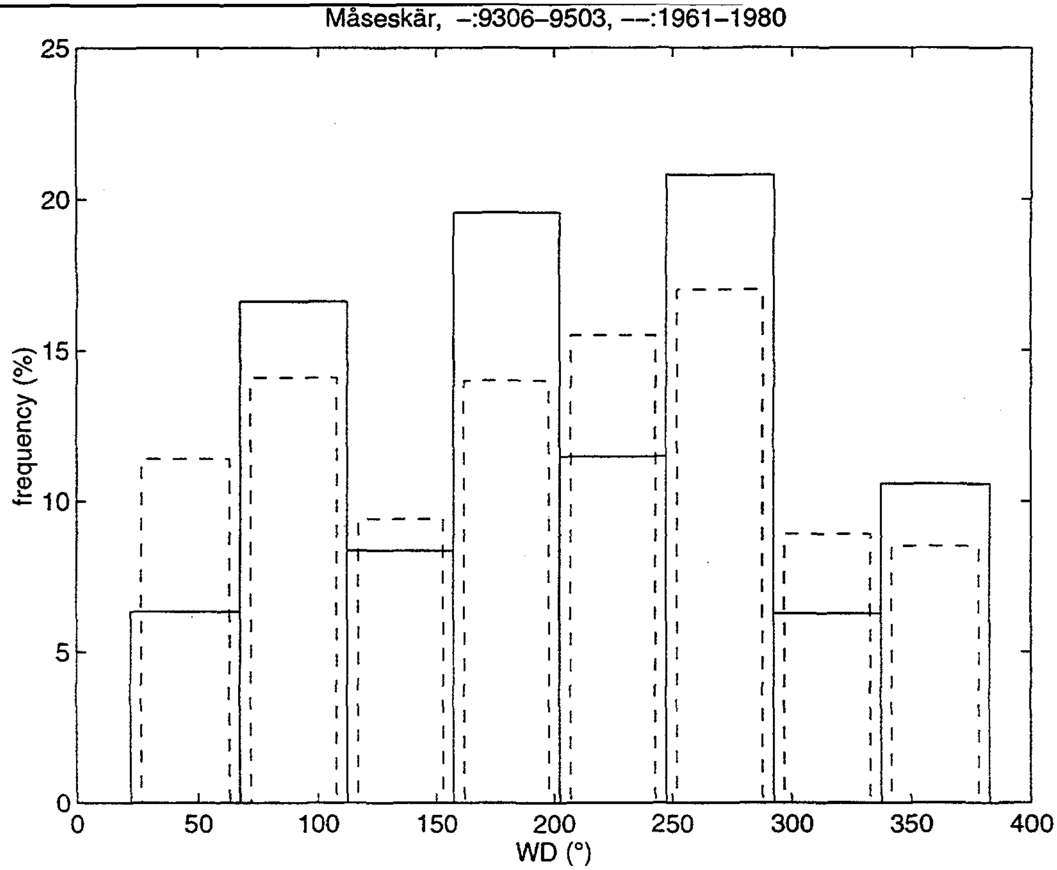


Figure 3.7:5. Observed wind direction distribution at Måseskär during the period 9306-9503 given by the full line bars. The dashed line bars give the climatological distribution 1961-1980.

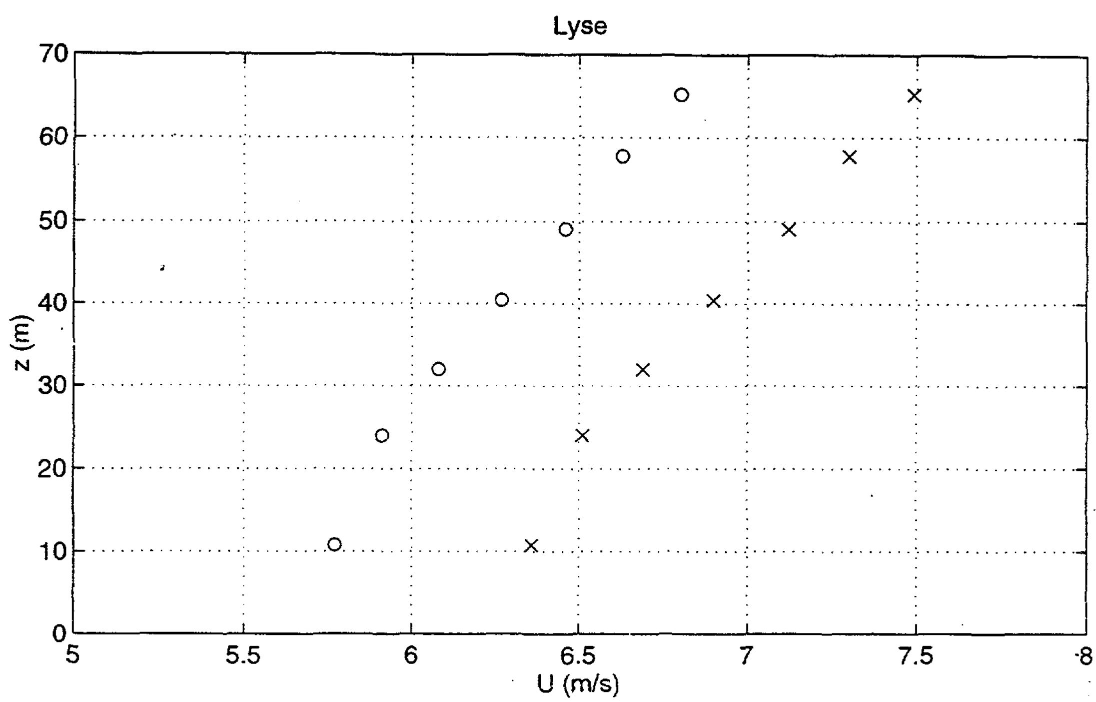


Figure 3.7:6. Mean wind profiles at Lyse - x: 9306-9503, o: climatological mean wind profile estimated using data from Måseskär 1961-1980.

4 ENVIRONMENTAL IMPACT

Environmental issues are becoming more and more important when planning and building wind power stations. Information to and acceptance by the public is crucial for a successful project. The three sections below is a summary of our experiences. The involvment of the general public in the project is also discussed in section 1.2.1 above.

4.1 NOISE

4.1.1 Introduction

Noise is an important environmental impact parameter for wind power stations and must be considered in planning situations. The minimum distance between wind power stations and dwellings is in many situations given by noise. Noise measurements were performed at Lyse to determine the emitted acoustic power of each unit, noise emission, and the environmental impact, noise immission, at the nearest houses.

Noise emission measurements were carried out to investigate the emitted acoustic power, sound power level, of the two units. Noise emission measurements were performed at each wind power station separately. The noise from a wind power station is a combination of aerodynamic noise from the blades and mechanical noise from the gear, generator and electric system. The Bonus and the NWP wind power stations are of different design, three blades with constant rotational speed compared to two blades with variable speed. The Bonus has a sophisticated vibration insulation of the gear from the tower, hub and blades to eliminate the radiation of mechanical noise.

Noise imission, sound pressure levels, have been measured at the nearest houses, approximately 400-500 m from the wind power station. The sound pressure levels at the houses are given mainly by the acoustic power of the units and the distance between the units and the houses.

4.1.2 Noise emission measurements

A comparison of the Sound Power Level vs. Wind Speed for the two units are presented in Figure 4.1:1.

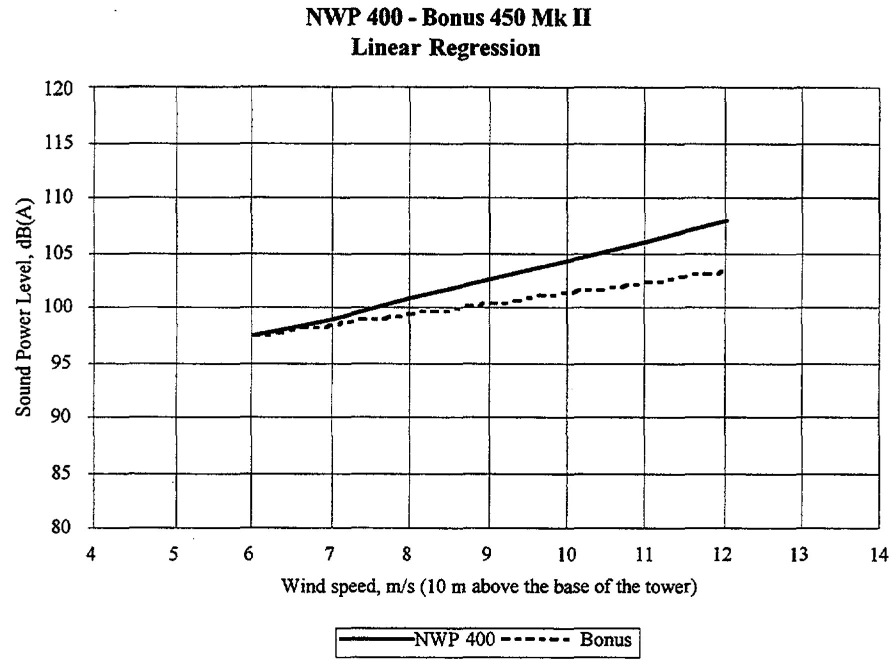


Figure 4.1:1 Sound Power Levels vs. Wind Speed.

The Sound Power Level of the Bonus 450 is approximately 2 dB(A) lower than the level from the NWP 400 at a wind speed of 8 m/s.

The characteristics of the noise from the two turbines was different. Aerodynamic noise from the blades dominated near the Bonus 450. Mechanical noise from the gear and the generator dominates near the NWP 400, especially at low wind speeds.

4.1.3 NWP 400. Noise emission

Sound Power Levels at different wind speeds are presented in Figure 4.1:2. The Sound Power Level at reference conditions, 8 m/s (10 m above the base of the tower) was determined to 101 dB(A).

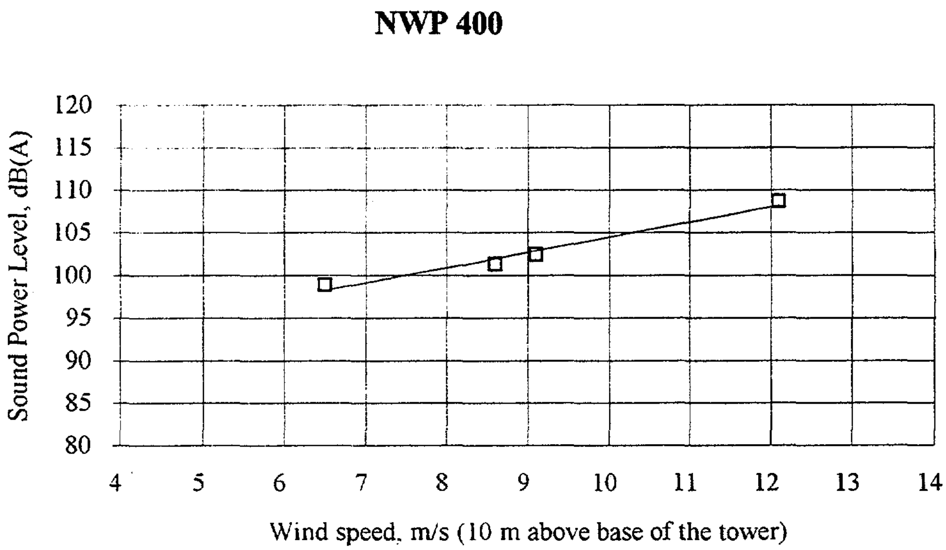


Figure 4.1:2 Sound Power Level vs. Wind Speed.

Audible tones are generated by the gear and the generator, especially at low wind speeds. The tones are radiated from the steel tower. An example of frequency analysis is shown in Figure 4.1:3.

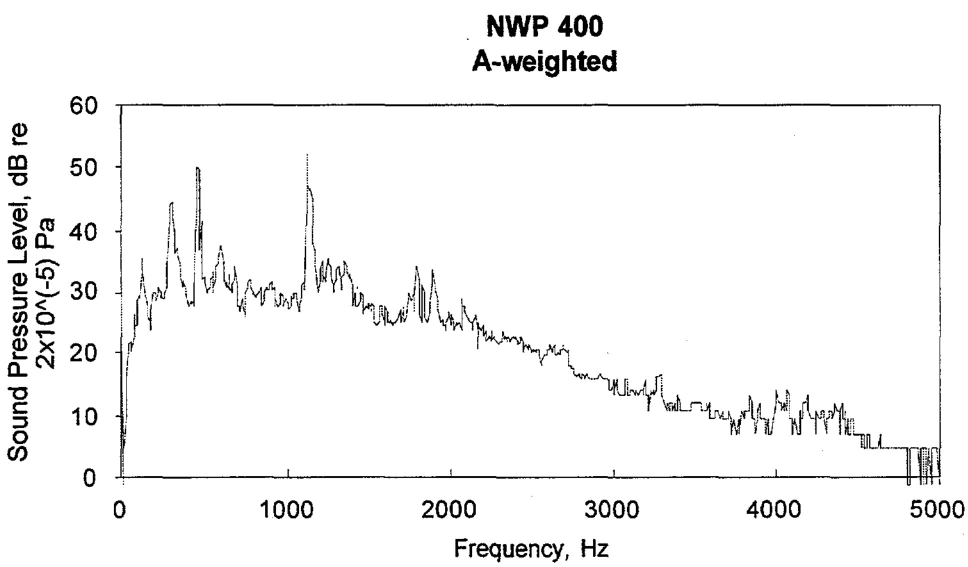


Figure 4.1:3 Example of narrow band frequency analysis (resolution 6,25 Hz, Hanning window) of the sound pressure level at a point on the ground 72 m from the hub. Wind speed: 8 m/s (10 m above base of the tower).

4.1.4 Bonus 450 MK II. Noise emission

Sound Power Levels at different wind speeds are presented in Figure 4.1:4. The Sound Power Level at reference conditions, 8 m/s (10 m above the base of the tower) was determined to 99 dB(A).

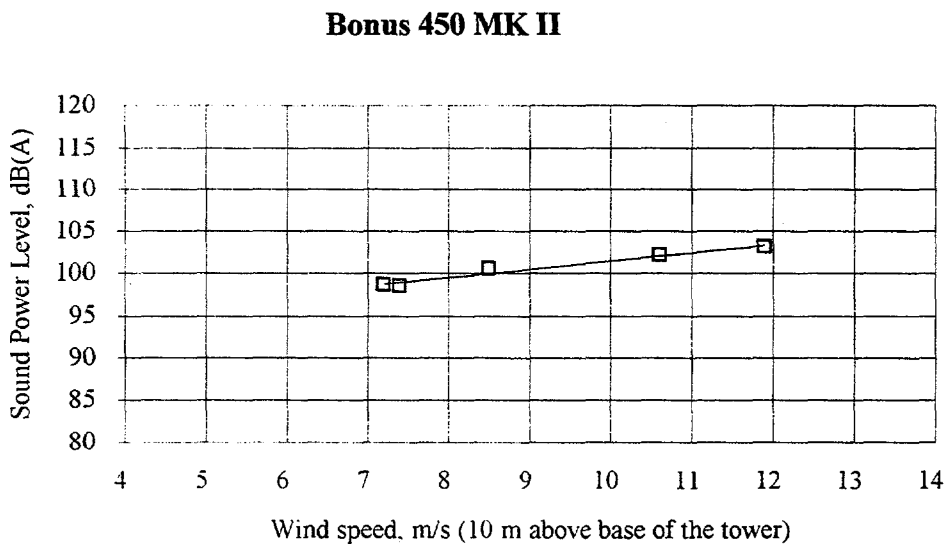


Figure 4.1:4 Sound Power Level vs. Wind Speed.

Audible tones were not heard at a distance larger than 50 m from the tower. Aerodynamic noise from the blades dominates. An example of frequency analysis is shown in Figure 4.1:5.

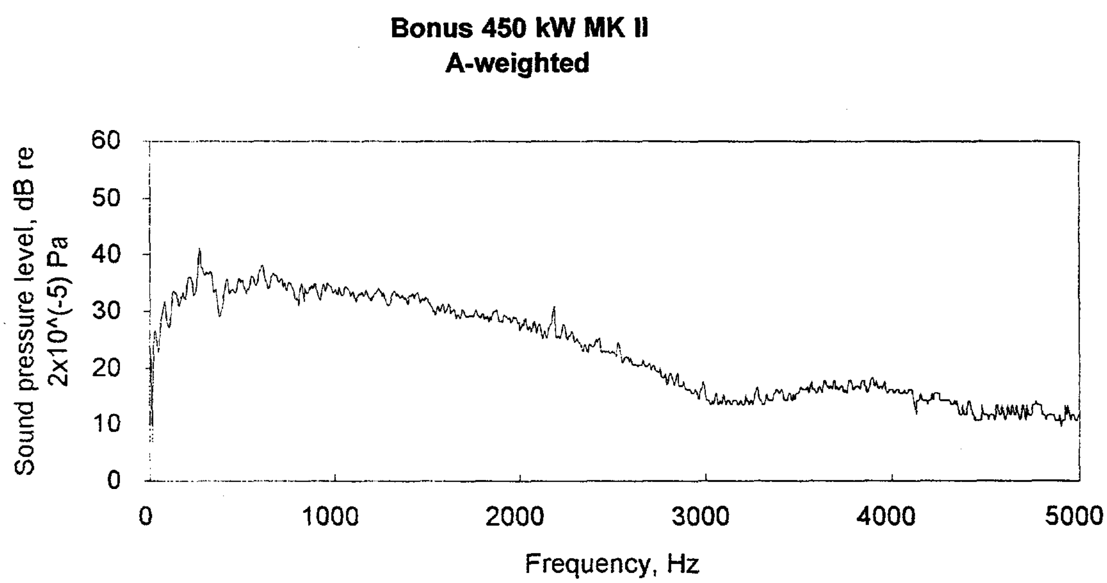


Figure 4.1:5 Example of narrow band frequency analysis (resolution 6,25 Hz, Hanning window) of the sound pressure level at a point on the ground 72 m from the hub. Wind speed: 8 m/s (10 m above base of the tower).

4.1.5 Noise immission. Sound Pressure Levels in the surroundings

The wind power station is situated on an "island". The distance from the station to the nearest houses is approximately 400 m. The sound pressure levels were calculated during the planning phase with estimated sound data for the turbines. Free field propagation over reflecting plane was assumed. Damping caused by air absorption was estimated to 3,5 dB(A) / 1000 m.

Sound pressure levels were measured at three points 1,5 m above ground approximately 400-500 m from the power station and compared with the previously calculated levels. Se Figure 4.1:6.

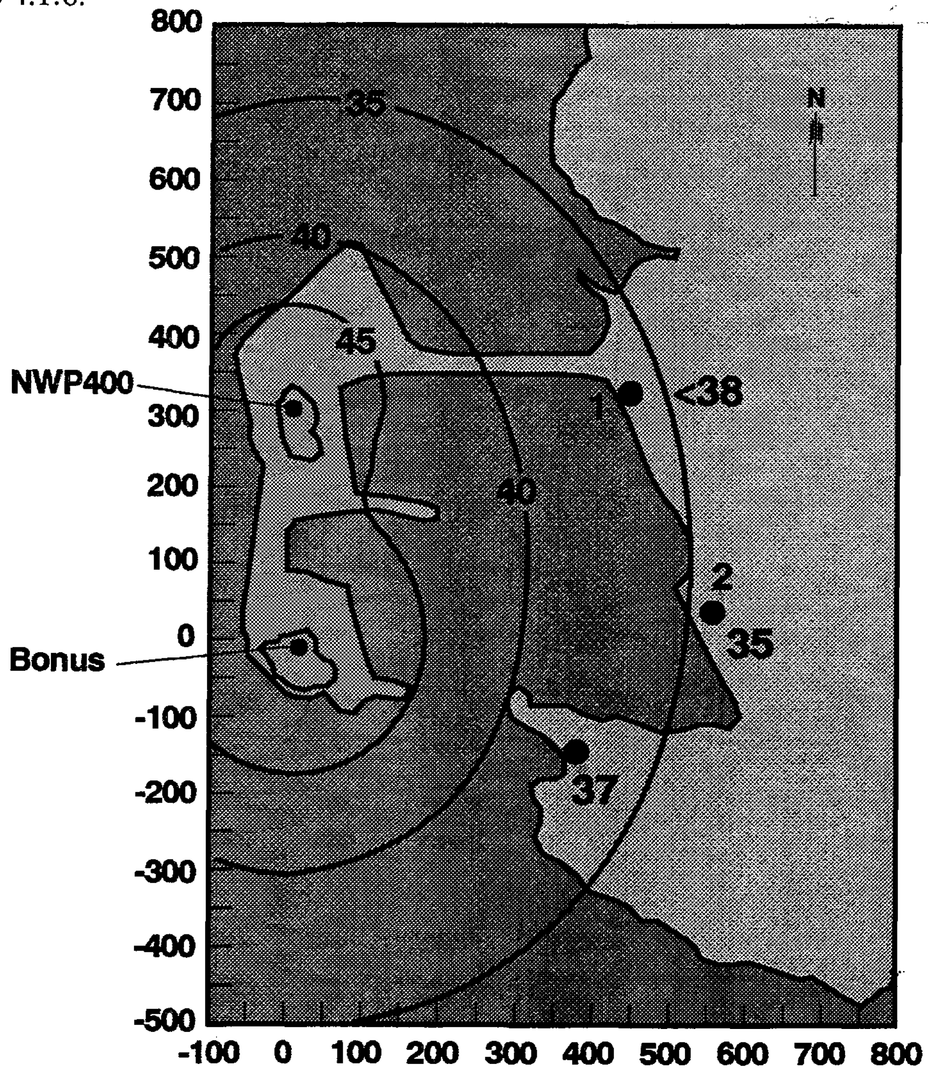


Figure 4.1:6 Calculated and measured Sound Pressure Levels in the surroundings. Wind speed 5 m/s. Wind from the south at measurements.

The measured sound pressure levels were low and in good agreement with the calculated values. Noise from the wind power station was audible at the measurement positions. The background level was very low. The area around the wind power station was dominated by cliffs and a "lagoon" with calm water at most wind directions, which gave a low background noise level from natural sounds. The masking from natural sounds was lower at the nearby houses in Lyse than at most other places.

Noise from Bonus 450 was dominating at point 3 (where the highest levels were measured). The distance from point 3 to Bonus was much shorter than to NWP. Audible tones were not heard at any of the measurement points.

4.2 ELECTROMAGNETIC INTERFERENCE

4.2.1 Background

Wind turbines can disrupt electromagnetic signals from radio and TV-transmitters, radio repeaters, radar signals and instrument landing systems. Both tower and rotating blades may be the source for such disturbances.

TV-reception was considered to be the only possible cause for electromagnetic interference at this specific location. Therefore a study was performed in order to investigate the effect of the turbines on the TV reception. Measurements were taken at two different occasions. The first one before the turbines were built and the second one after they were erected.

Seven representative locations, close to settlements, were chosen. Distances from the turbines ranged from 600 to 2200 metres. Measurements were also taken directly below the turbines, at 100-300 distances.

4.2.2 Conclusions

The following conclusions were drawn from the measurements:

- Measurement values and picture quality at settlements (600-2200 m) showed no influence from the wind turbines.
- Minor disturbances were noted at 1100 metres. However, these were considered to have small influence on the signal quality.
- Disturbances were related to rotor RPM and number of blades
- In the vicinity (100-300 M) of the WECS there were strong to moderate disturbances. These showed up as jumping frames and hissing sound.
  - Disturbances were stronger on the UHF band, channel 21-60, than on the VHF band, channel 5-12.
  - Disturbances were obtained when the signal passed through the turbine, but some minor disturbances were also noted "in front" of the turbine.

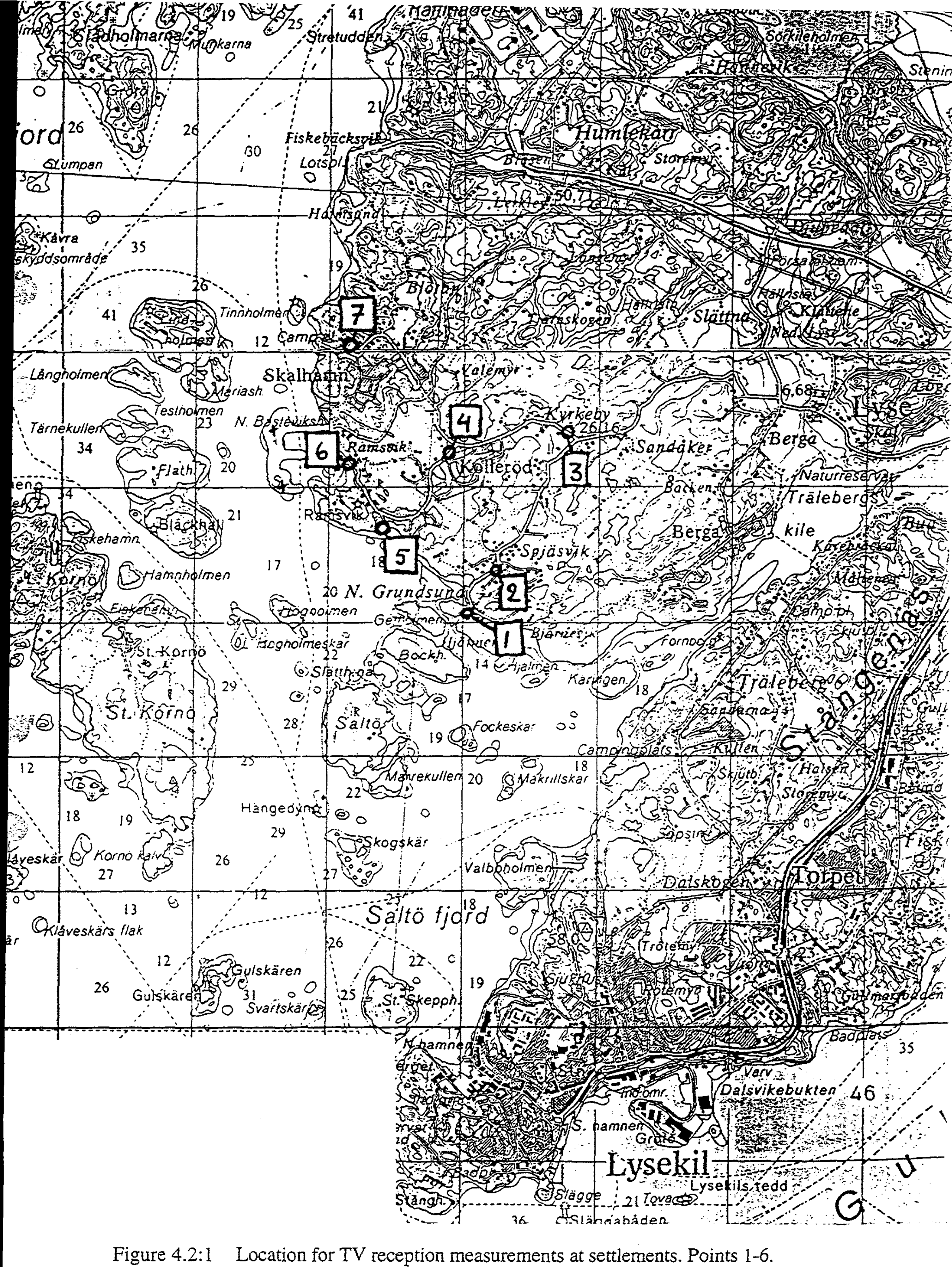


Figure 4.2:1 Location for TV reception measurements at settlements. Points 1-6.

4.3 PUBLIC ACCEPTANCE

4.3.1 Background

The aim of this study was to present attitudes and opinions regarding the Lyse Wind Power Station, and also to illuminate how the public experienced this project. Lyse Wind Power Station is located at the Bastevik islets (Basteviksholmarna), north of Lysekil in the province of Bohuslän (see Figure 4.3:1). In the vicinity of the Bastevik islets two areas have been chosen where the method of qualitative interviews was conducted in order to grasp the public opinion and attitudes regarding the Lyse Wind Power Station. In Skalhamn 20 interviews were made with people living permanently in the area, and in Ramsvik 24 summer guests were interviewed. In these areas the living distance from Lyse Wind Power Station vary between 350-4000 meters. Six officials in the city of Lysekil act as a group of reference to the study.

The visual impact of these two units mostly differ as regards the number of turbine blades; the Bonus unit has three and the NWP has two. There is also a difference regarding the obstacle marking. The tips of the turbine blades are red on the Bonus unit. See Figures 1.2:2, 1.3:2 and 1.3:3

The key questions placed to the public and officials in this study were:

- Looking at Lyse Wind Power Station, do you have any preferences regarding the design of the two units?
- Is there anything that you have experienced as disturbing regarding the design of the two units?
- Have you experienced any problems with noise originating from Lyse Wind Power Station?
- Do you find the information regarding Lyse Wind Power Station adequate?
- Is there any further information that you request?
- Do you discuss wind energy with friends and acquaintances?
- Do you hold a more positive view towards wind energy after having experienced it in your own personal surroundings?
- Do you find wind power agreeable to this type of landscape?
- Do you find that Lyse Wind Power Station has been a positive experience?
- Do you think that wind energy is an important part to develop in the Swedish energy system?
- What experience is the most important to gain from a project such as Lyse Wind Power Station?
- Who should hold the largest responsibility for the development of Swedish wind energy?

The results from each geographical area are presented under headlines summarising the above listed key questions. The conclusions drawn from this study are presented at the very end.

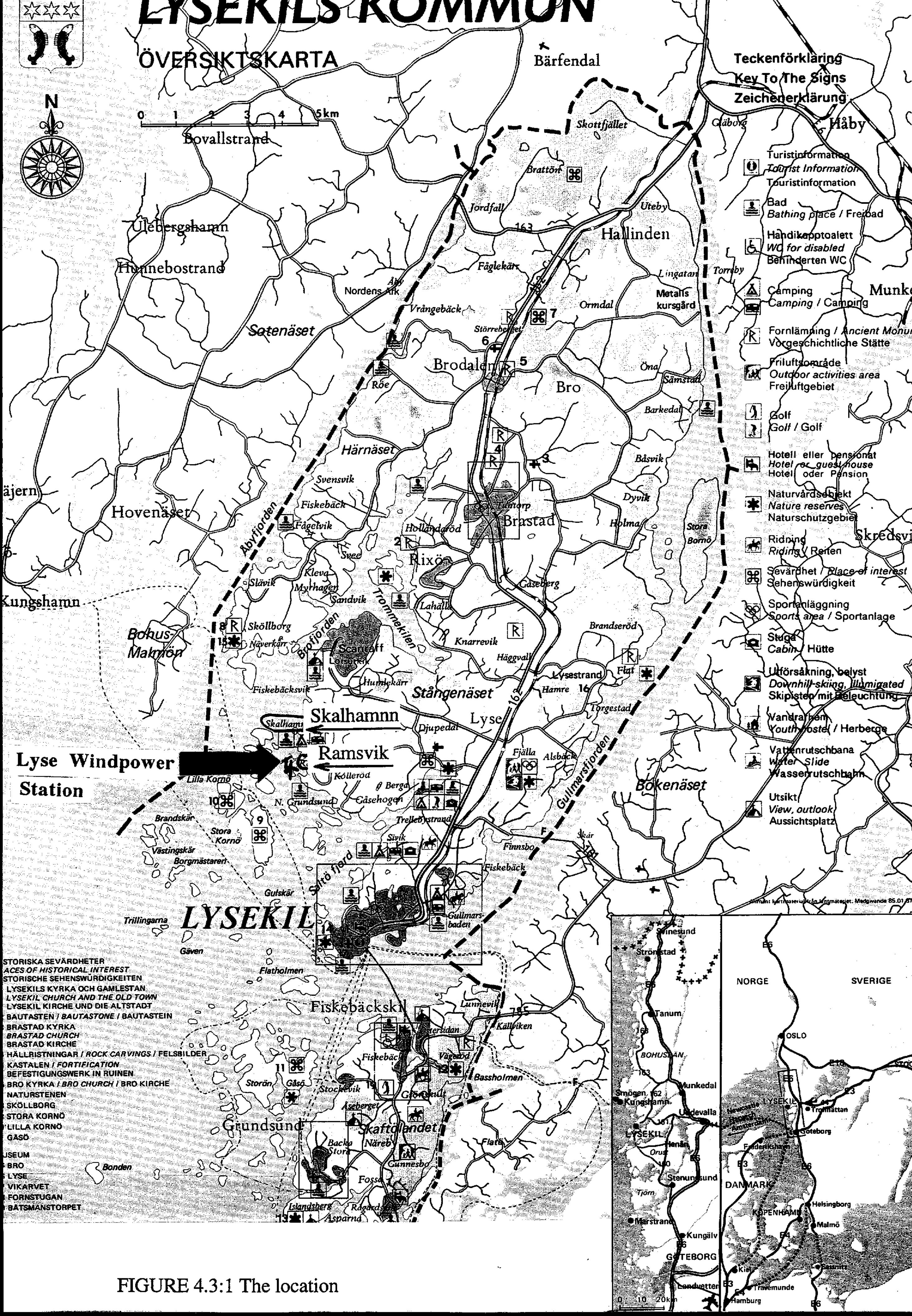


FIGURE 4.3:1 The location

4.3.2 Results

Six officials were interviewed in the city of Lysekil, and these persons constitute a group of reference to this study. This group actively participated in the planning and preparatory work for the realisation of Lyse Wind Power Station. In Skalhamn 20 persons living permanently in the area were interviewed. In this group the distance from Lyse Wind Power Station varies between 500-4000 meters. Ramsvik is located in the immediate vicinity of Lyse Wind Power Station and in this area 24 summer guests were interviewed, living 350 -1000 meters from the site.

4.3.2.1 Visual impact and disturbance from Lyse Wind Power Station

The majority in all groups prefer three turbine blades to two in this study. The reason is that three turbine blades seem to be more in harmony and create a more balanced impression. A recurrent motivation for this preference was also that the Danish unit seems to work much better. Since the majority of the interviewed persons were aware of the fact that Lyse Wind Power Station aims to test new technology, one feels (mostly officials) that this opinion to a certain degree needs to be excused by a conventional disposition, (sv. konventionell läggning), of the interviewed persons.

The majority in all areas experienced no disturbance from hinder markings or noise. A certain swishing sound was heard but this is not apprehended as noise, and this sound was most of the time camouflage by the sea and the wind. Remarks regarding sound, landscape or noise disturbance are expressed mostly in Ramsvik by the summer guests living in the immediate vicinity of Lyse Wind Power Station. These hesitations might be overcome if it was possible to distribute wind energy directly to those living close by wind power sites.

4.3.2.2 Information

The information regarding Lyse Wind Power Station was carried through very well. To erect an information building at the site was considered as a good idea but one felt that it is too small for a group of visitors. The co-operation between the tourist information and Vattenfall should be extended and the energy production should be displayed and distributed in a more accessible manner. Information regarding shutdown in the production from the Swedish unit was requested by all groups.

4.3.2.3 Discussion

The awareness of wind power increased in the municipality of Lysekil. People gained more knowledge and their curiosity was triggered by a general interest in alternative energy production and by the fact that it is now possible to experience wind energy production at close range. There were some remarks regarding the Swedish unit which experienced frequent shutdowns, and this calls for a clarification of the reason for these shutdowns. Further, it needs to be clarified why one choose to locate a well tested unit together with a new Swedish prototype.

There was an interest in the municipality plans for further wind power sitings in both Ramsvik and Skalhamn. The officials and those living permanently in the vicinity of Lyse Wind Power Station expressed speculations regarding problems with acceptance among the summer guests. These speculations were to a certain degree confirmed by the hesitations found among the interviewed summer guests in Ramsvik regarding further wind power locations in the province of Bohuslän. The summer guests felt that it would of course be more beautiful without wind power. However, it seems that their understanding and regarding the development of renewable energy sources outweigh their hesitations.

4.3.2.4 Opinion about and experience of wind energy in the landscape

Lyse Wind Power Station has given the municipality an environmental profile and illuminates how Lysekil takes active part in the development of renewable energy sources. People now know "what it is all about" and they know that wind energy production can be handled by the municipality. There was a general positive attitude towards wind energy, however, certain reservations exist regarding the sensitive and very unique landscape. It was often emphasised that environmental concern is an essential part of the planning and location of wind power production sites, which means that certain areas must remain untouched. The visual impact was a very important factor which must be of prime concern when choosing a location and the number of units. Public opinion must play an important part along with the development of know-how. The majority of interviewed persons felt that their positive attitude towards wind energy was confirmed through their experiences of Lyse Wind Power Station. Their contact with Vattenfall and Lyse Wind Power Station was a positive experience.

4.3.2.5 The importance of wind energy in Sweden

The majority of the interviewed persons felt that wind energy is an important complement to the Swedish energy system. The large power companies play an important part in the development and testing of new technology, private interests are, however, of equal importance. The manufacturers of wind power plants must be stimulated to develop more efficient units.

4.3.4 CONCLUSIONS

Lyse Wind Power Station triggered a growing concern for wind energy development and production in the municipality of Lysekil. Certain hesitations among the summer guests in Ramsvik (living in the immediate vicinity of the wind power station) were expressed regarding wind power locations in their vacation environment. These hesitations might be overcome if it was possible to distribute wind energy directly to those living close by wind power sites. Also, a frequent and accessible distribution or display of production results might increase the public acceptance.

Wind Power locations must be chosen in co-operation with the public and in consideration of the affected environment. The number of production units at one location must be decided by the same factors. Certain areas must remain untouched. The wind technology must be developed so that more energy can be produced by fewer units.

In Ramsvik some disturbing noise was reported. However, there was no clear connection between shortest living distance and reported disturbance. A majority of the interviewed persons in this study expressed a positive attitude toward wind energy in general, and this can to a certain extent explain their positive experience of Lyse Wind Power Station.